ASSESSEMENT OF RADIUM, RADON AND THEIR PROGENY IN HUMAN ENVIRONMENT USING SOLID STATE NUCLEAR TRACK DETECTORS

ABSTRACT
OF THE
THESIS

SUBMITTED FOR THE AWARD OF THE DEGREE OF

Doctor of Philosophy

IN

APPLIED PHYSICS

BY

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UNDER THE SUPERVISION OF

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ALIGARH MUSLIM UNIVERSITY
ALIGARH (INDIA)
DECEMBER, 2013

ABSTRACT

Radon is a natural radioactive gas occurs as a product of uranium decay. It is an unstable radionuclide that disintegrates through short lived decay products before eventually reaching the end product of stable lead. The presence of high levels of radon in indoor environment constitute a major health hazard to general population. The radon progeny is a well established causative agents of lung cancer and other types of cancers. The lung cancer risk is much higher when radon exposure is combined with smoking. According to the Biological Effects of Ionizing Radiations (BEIR) report, smokers were 10 times more likely to get lung cancer risk than non-smokers. Recognizing the importance of radon as a public health issue, large-scale national and International radon-programs were initiated world-wide, such as the International Atomic Energy Agency (IAEA) coordinated research program CRP 'Radon in the Human Environment' involving over 50 countries and the International Radon Project (IRP) by World Health Orgaization (WHO) on public health aspects of radon exposure. The primary goal of the present research work is to assess the level of radon, radium and their progeny in the indoor and outdoor environment, to compare the concentration with other locations and to determine the radon exhalation rate from soil samples.

The present research work has been divided into five chapters and has contents briefly outline below.

Chapter I of the thesis have general introduction of natural radioactivity, external and internal exposure, occurrence of radon and thoron and the probable health hazards due to these radionuclides. A brief description of effect of metrological parameters on radon levels, radiation terms and units also given in this chapter.

Chapter II of the thesis gives an account of various active and passive techniques for the radon measurements. It also discuss different types track detectors, merit and

demerits of solid state nuclear track detectors (SSNTD's). SSNTD's have been widely used for measuring the passive time integrated radon, thoron, their progenies and exhalation rates. This chapter also include the various track formation mechanism, track registration criteria, methods of track revelation and visualization and the information about the geology, climate conditions and the characteristics of the dwellings surveyed.

Chapter III of the thesis depicts the results of the study related to radon, thoron and their progeny. Indoor radon measurements have been carried out at Farrukhabad, Faizabad, Bareilly situated at the northern part of India and Nasik in the western part of India. The effective dose and the life time fatality risk due the inhalation of radon and its progeny have also been calculated. Investigation show that the Bareilly has higher level of radon as compared to Farrukhabad and Faizabad.

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I dedicate this thesis to
my parents for their constant support and unconditional love.

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Certificate

This is to certify that the thesis entitled **"Assessment of Radium, Radon and Their Progeny in Human Environment Using Solid State Nuclear Track Detectors"** submitted by Mr. Deepak Verma to the Department of Applied Physics, Faculty of Engineering & Technology, Aligarh Muslim University, Aligarh for the award of the degree of Doctor of Philosophy has been carried out under my supervision and guidance.

I, further certify that Mr. Deepak Verma has fulfilled the requirements of Aligarh Muslim University, Aligarh for the submission of Ph.D. thesis.

Dr. Pushpendra Tripathi
(Supervisor)

Deepak Verma
(Research Scholar)

DECLARATION

I declare that this thesis entitled **"Assessment of Radium, Radon and Their Progeny in Human Environment Using Solid State Nuclear Track Detectors"** submitted in partial fulfillment of the degree of **Doctor of Philosophy** is a record of original work carried out by me under the supervision of **Dr. Pushpendra Tripathi**, and has not formed the basis for the award of any other degree or diploma, in this or any other Institution or University. In keeping with the ethical practice in reporting scientific information, due acknowledgements have been made wherever the findings of others have been cited.

(Deepak Verma)

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Place: Aligarh **(Deepak Verma)**

Date: En. No. GA 0275

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LIST OF ABBREVIATIONS

Bq	:	Becquerel
M	:	Meter
mSv	:	milli Sievert
y	:	year
kg	:	kilogram
d	:	day
rem	:	*roentgen equivalent man*
MeV	:	Mega (Millions) electron Volt
pCi	:	pico Curies
l	:	liter
h	:	hour
km	:	kilometer
cm	:	centimeter
s	:	second
^{0}C	:	degree Centigrade
kPa	:	kilo Pascal
μ	:	micro
min	:	minutes
DNA	:	Deoxyribo Nucleic Acid
Ω	:	ohm
+ve	:	positive
N	:	North
E	:	East
mg	:	milligram

CHAPTER-I

INTRODUCTION

1.1 Radiation

Radiation comes from outer space, the ground, and even from within our own bodies. Radiation is simply a part of our daily life. The word, "radiation" generally brings to mind nuclear power plants, nuclear weapons or medical diagnostics and treatments. Nonetheless, we routinely encounter a variety of radiation sources every day, for example, smoke detectors, household appliances, electrical power lines, and even the sun. Radiation is the energy that travels in the form of waves or high speed particles and it makes up the electromagnetic spectrum. The electromagnetic spectrum is divided into two major categories; ionizing radiation and non-ionizing radiation. Ionizing radiation has enough energy to break chemical bonds in molecules or remove tightly bound electrons from atoms, thus creating charged molecules or atoms (ions). The sources of these radiations are natural as well as man-made, but the naturally occurring radiations are the major contributor to the environment radiation (figure 1.1). These radiations are composed of cosmic rays and terrestrial radiations [UNSCEAR, 1988; IAEA, 1990]. There are four major types of ionizing radiation; alpha particles, beta particles, gamma rays and x-rays. On the other hand non-ionizing radiation has energy to move electron around the atoms in a molecule or cause them to vibrate, but not enough to remove them. Table 1.1 presents the radioactivity present in some natural and man-made substance [Azam, 2002].

1.1.1 Alpha Particles

Alpha Particles are energetic, positively charged (helium nuclei) and commonly formed in the radioactive decay of the heavy radioactive elements such as uranium and radium as well as some man-made elements.

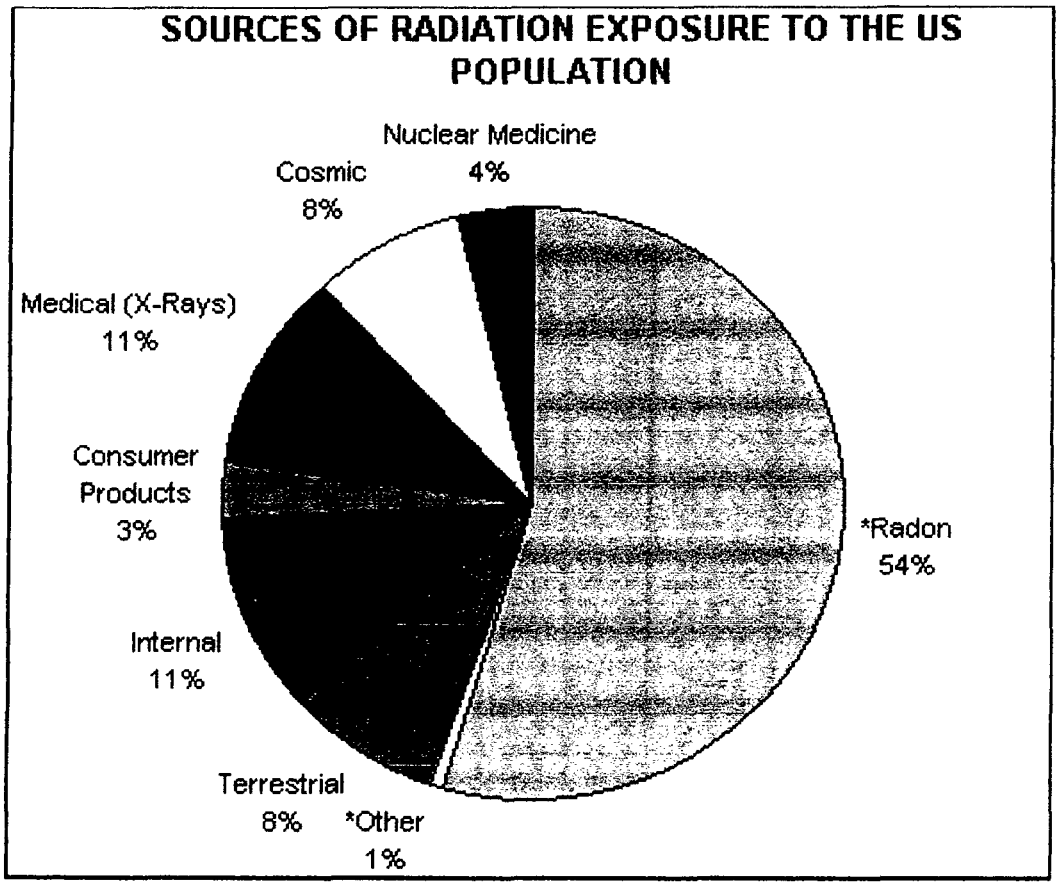

Figure 1.1 *Sources of radiation exposure to US population [NCRP, 1987]*

Table 1.1 Radioactivity in some natural and man-made substance [Azam, 2002]

Item	Activity in Bq
1 Loaf of bread	70
1 kg of coffee	10×10^2
1 Adult human	70×10^2
1 kg of granite	10×10^2
1 kg of coal ash	20×10^2
1 kg of uranium	25×10^6
1 household smoke detector	30×10^3
1 kg super phosphate fertilizer	50×10^2
Radioisotope for medical therapy	10×10^{13}
Radioisotope for medical diagnosis	70×10^6
1 kg of low level of radioactive waste	10×10^5

They rapidally lose their energy when passing through a matter but do not penetrate very far; however, they can cause damage over their short path through tissue. These particles are usually completely absorbed by the outer dead layer of the skin and can be harmful if they are ingested or inhaled. Alpha particles can be stopped completely by a sheet of paper.

1.1.2 Beta Particles

They are fast moving, positively or negatively charged electrons emitted from the nucleus during radioactive decay. Several man-made and natural sources such as tritium, carbon-14, and strontium-90 emitted beta particles from which humans are exposed. Beta particles are more penetrating than alpha particles, but are less damaging over equal travelled distance. Some beta particles are capable of penetrating the skin and causing the radiation damage however, as with alpha emitters, beta emitters are more hazardous when they are inhaled or ingested. Beta particles traveles appreciable distances in air, but can be reduced or stopped by a layer of clothing or by a aluminum sheet of few millimeters.

1.1.3 Gamma Rays

Similar to visible light and X-rays, gamma rays are the weightless packets of energy called photons. These rays often accompany with the emission of alpha or beta particles from a nuclei. They have neither a charge nor a mass and are very penetrating. Naturally occurring potassium (^{40}K) is one of the source of gamma rays in the environment whereas manmade sources include plutonium-239 and cesium-137. Gamma rays can easily passes through the human body or absorbed by tissue, thus constituting a radiation hazard for the entire body. Several feet of concrete or a few inches of lead required to stop the most energetic gamma rays.

1.1.4 X-rays

X-rays are high energy photons produced by the interaction of charged particles with matter. These rays have the same properties as the gamma rays, but differ in origin i.e. X-rays are emitted from process outside the nucleus, while gamma rays originate from inside the nucleus. X-rays are generally lower in energy and therefore less penetrating than gamma rays. Literally thousands of X-ray machines are used daily in medical science industry for examinations, inspection and process controls. X-rays are also used for cancer therapy to destroy malignant cells. Because of their many uses, X-rays are the single largest source of man-made radiation exposure. They can be stopped by a few millimeters of lead.

1.2 Natural Radiation

The sources of natural radiation are cosmic rays and natural substances existing in the earth itself and inside the human body. It has been estimated that about 85% of the radiation to which humans are exposed is coming from natural sources and the remaining 15% is from man-made sources [UNSCEAR, 2000]. Therefore we can say, most of the ionizing radiation to which people are exposed comes from natural rather than man-made sources. Natural sources that account for exposure to the environmental radiation include radon (59%), terrestrial gamma rays (19%), cosmic rays (12%), and water and food (10%). The annual effective dose for adults from natural sources present in table 1.2. Terrestrial gamma radiation dose rates vary mainly with geology, building materials, dwelling type and age of the building [Billon et al., 2005]. The worldwide average value of effective dose due to the natural radiation sources is 2.4 mSv [4]. Few areas in the world, where the radiation dose is high are known as high background radiation areas (HBRAs). In these areas the local geological controls and geochemical effects cause enhanced levels of terrestrial radiation [UNSCEAR, 2000; UNSCEAR,

1993]. Very high background radiation areas are found at Guarapari, coastal region of Espirito Santo and the Morro Do Forro in Minas Gerais in Brazil [Paschoa, 2000; Bennett, 1997]; Yangjiang in China [Wei and Sugahara, 2000]; southwest coast of India [Sunta et al., 1982]; Ramsar and Mahallat in Iran [Sohrabi, 1998] and in the United States and Canada [NCRP, 1987].

The interactions of cosmic-ray particles in the atmosphere produce a number of radionuclides, including ^{3}H, ^{7}Be, ^{14}C and ^{22}Na. These nuclides are called cosmogenic nuclides. Naturally occurring radionuclides of terrestrial origin (also called primordial radionuclides) are present in various amounts in the environment, including the human body itself. The radionuclides with half-lives comparable to the age of the earth and their decay products exist in significant quantities in different types of materials. Secondary radionuclides are radiogenic isotopes derived from the decay of primordial radionuclides. They have shorter half-lives than primordial radionuclides. Natural environmental radiation depends on geological and geographical conditions [Klement, 1982].

Irradiation of the human body from external sources is mainly due to the gamma radiations emitted from radionuclides produced in the uranium (^{238}U), thorium (^{232}Th) and from ^{40}K series. These radionuclides are also present in the body and irradiate the various organs with alpha and beta particles, as well as with gamma rays. Some other terrestrial radionuclides (including those in the ^{235}U series) ^{87}Rb, ^{138}La, ^{147}Sm and ^{176}Lu, exist in nature but at such low levels that their contribution to the human dose is negligible. Terrestrial radionuclides present at trace levels in all soils, however, the specific levels are related to the types of rock from which the soils originate. Higher radiation levels are associated with igneous rocks such as granite and lower levels with sedimentary rocks [Faure, 1986].

***Table 1.2** Annual effective doses to adults from natural sources [UNSCEAR, 1993]*

Sources	**Annual effective dose (mSv)**
Extraterrestrial radiation	
Cosmic ray	0.38 (16.1%)
Cosmogenic radiation	0.01 (0.42%)
Terrestrial radiation	
External exposure	0.46 (19.5%)
Internal exposure	0.23 (9.77%)
Radon and its progeny	
Inhalation	1.2 (51.0%)
Ingestion	0.005 (0.21%)
Thoron and its progeny	
Inhalation	0.07 (3.0%)

The activity concentration of ^{40}K in soil is an order of magnitude higher than that of ^{238}U or ^{232}Th. Building materials contribute to the gamma radiation, mainly from ^{40}K, ^{226}Ra, ^{232}Th and their progenies respectively. Radioactivity levels in various building materials such as soil, sand, etc. have been reported by many workers from different geological regions in the world [Beretka and Matthew, 1985; Zikovsky and Kennedy, 1992; Tahir et al., 2005]. Natural radioactivity in soil depends on soil type, mineral makeup and density. These radionuclides are also part of food cycle and they present in variable amount in different types of consumer items. The level of uptake depends on the physical and chemical properties of the radionuclides and also on the environmental matrix of interest. In order to measure the concentration of these primordial radionuclides and the dose delivered from it, various types of instrument are used. These primordial nuclides are generally detected by the gamma rays emitted by them.

1.3 Man-made Radiation

The most common and unavoidable manmade radiation comes from medical sciences. X-ray is the commonest form of medical radiation. There is hardly any inhabitant who has not had an x-ray picture in their life. One chest x-ray gives a dose of 0.2 mSv. X-ray investigation of body process such as barium meal to diagnose certain intestinal ailments gives a dose between 1-10 mSv. A typical cancer treatment gives a dose of about 1000 mSv, usually spread over several weeks. In such cases great care is taken to face the radiation precisely onto the affected part so that damage to the corresponding tissue is kept as low as possible. Nuclear weapon tests and nuclear reactor accidents are also the main sources of environmental man-made radioactivity. Radionuclides formed as a result of these nuclear activities can reach humans by entering their food chains [Birattari et al., 1991]. After the Chernobyl nuclear reactor accident, particles larger than 10 mm were deposited around the power plant while the smaller ones

were transported to northern hemisphere when the meteorological conditions allowed [Appleby and Luttrell, 1993]. It has been estimated that cesium (^{137}Cs) will remain in the environment at measurable contents throughout the next 200–300 years [Iskander et al., 2000]. Soil is the main reservoir of man-made radionuclides formed by nuclear activities. ^{137}Cs deposited in soil causes internal irradiation by inhalation and by ingestion of contaminated food, or secondly, through external irradiation by photon emissions from surface soil [Bunzl, 2002]. Radiation is used on an ever increasing scale in medicine, dentistry and in industry. Other sources of man-made radiation include the radioactive materials which are used in common consumer products such as digital and luminous-dial wristwatches, ceramic glasses, artificial teeth, and some smoke detectors.

1.4 Effect of Radiation Exposure

Ionizing radiation affects people by depositing energy in body tissue, which can cause cell damage or cell death. In some case there may be no effect while in other cases the cell may survive but become abnormal, either temporarily or permanently, and an abnormal cell may become malignant. Large doses of radiation can cause an extensive cellular damage and result in death. Whereas the person or particular irradiated organs exposed with the smaller dose may survive, but the cells are damaged, increasing the risk of cancer. The extent of the damage depends upon the total amount of energy absorbed, the time period, dose rate of exposure and the particular organ exposed. It should be noted that the health effects caused by radiation exposure can also occur in an unexposed person due to some other causes. There are two types of radiation effect.

1.4.1 Prompt Effects

These effects occur when a large/single dose of radiation or a series of doses given for a short period of time. High doses can result from accidental or emergency exposure or from a special medical procedure (medical therapy). In most of the cases,

these effects can cause both immediate and delayed effects. For human and other mammals, if the dose is large enough then it can cause rapid development of radiation sickness, evidenced by gastrointestinal disorders, bacterial infections, hemorrhaging, anemia, loss of body fluids, and electrolyte imbalance. Extremely high level of dose can result in death within a few hours, days or weeks. The effects of radiation dose to the humans are shown in table 1.3.

1.4.2 Delayed Effects

Evidence of injury from low or moderate doses of radiation may not show up for months or even years. The specific types of cancers associated with radiation exposure include leukemia, multiple myeloma, breast cancer, lung cancer and skin cancer. For leukemia, the minimum time exposure between the radiation exposure and the appearance of disease (latency period) is about 2 years. For solid tumors, the latency period is more than 5 years. Cataracts are induced when a dose exceeding approximately 200-300 rem is delivered to the lens of the eye. Radiation induced cataracts may take a time of several months to years to appear.

1.5 Benefits of Radiation

Radiation and radioactive materials can be used beneficially in a number of ways as given below:

1.5.1 Agriculture

The increase in the volume and quality of grains and cereals has been vastly improved by selectively growing superior strains labeled with radioactive isotopes. These improvements are helping to alleviate famine in third world countries.

1.5.2 Environmental Measurements

The movement of pollutants through the environment (its ground waters and rivers) can be accurately measured by the use of radioactive tracers.

Table 1.3 *Effect of radiation dose to the humans [NCRP, 1989]*

Effects	**Dose (rem)**
Blood count changes	50
Vomiting (threshold)	100
Mortality (threshold)	150
$LD_{50/60}$* (with minimal supportive care)	320 – 360
$LD_{50/60}$ (with supportive medical treatment)	480 – 540
100% mortality (with best available treatment)	800

*The $LD_{50/60}$ is that dose at which 50% of the exposed population will die within 60 days.

1.5.3 Eradication of Pests

A number of pest flies are no longer the problem that they were in California since their numbers have been cut drastically following the release of sterile male flies in the region.

1.5.4 Food

Food, such as beef and chicken, that has been sterilized by irradiation has a longer shelf life and is free of E. coli, a bacterium that has killed several children as a result of eating poorly cooked fast food hamburgers. An extension of food irradiation could save the lives of many children and would be particularly useful in developing countries where refrigeration is not available.

1.5.5 Generation of Electricity

The nuclear plants around the world (about 440) contribute approximately 16% of the world's electrical energy requirements. In U.S. about 109 plants, contributed 22% of the US's consumption of electricity in 2000.

1.5.6 Medical Diagnostics

The use of radiation in the medical science extends from X-rays, through Magnetic Resonance Imaging (MRI), to the use of radioactive tracers to diagnose such varied conditions as faulty thyroid glands or bone problems. The use of radioactive tracers often takes the place of invasive surgical diagnosis.

1.5.7 Oil Drilling

Isotopes are used to measure the quality of steam before it is injected into almost defunct oil wells to force out residual supplies.

1.5.8 Polymerization of Plastics

Plastic can be polymerized by radiation instead of damaging heat treatments. The polymerized plastics are used in such applications such as car dashboards, which would,

otherwise, crack badly under heat in the summer.

1.5.9 Quality Control of Metal Parts

The integrity of metal parts such as aircraft engine turbine blades can be verified by radiophotography on a conveyor belt instead of having to destroy a sampling of blades to ensure they are intact.

1.5.10 Research in Biology

The use of radioactive tracers allows the non-invasive tracking of elements and drugs through the body for both metabolic studies and medicine.

1.5.11 Space Power

When small amounts of power are needed in space in regions in which solar power is inefficient (on the dark side or when large solar panels are impossible), plutonium batteries are ideal producers of compact energy.

1.5.12 Treatment of Cancers

Cancerous cells can be selectively killed by the use of radioactivity, either in the form of direct beams, as for breast cancer, or as radioactive bullets that are designed to migrate directly to the cancerous cells that need killing. The only alternative, chemotherapy, which involves the use of invasive drugs, is a very difficult alternative for the patient.

1.6 Protection from Radiation

Although some radiation exposure is natural in our environment, it is desirable to keep radiation exposure As Low As Reasonably Achievable (ALARA) in an occupational setting. This is accomplished by the techniques of time, distance, and shielding.

1.6.1 Time

The shorter the time in a radiation field, the less the radiation exposure we will receive. Work quickly and efficiently. Plan our work before entering the radiation field.

1.6.2 Distance

The farther a person is from a source of radiation, the lower the radiation dose. Levels decrease by a factor of the square of the distance. Do not touch radioactive materials. Use remote handling devices, etc., to move materials to avoid physical contact.

1.6.3 Shielding

Placing a radioactive source behind a massive object provides a barrier that can reduce radiation exposure.

1.6.4. Administrative and Engineering Controls

The use of administrative and engineering controls is essential for keeping radiation exposure ALARA. We can work safely around radiation and/or contamination by following a few simple precautions.

a. Use time, distance, shielding and containment to reduce the exposure.

b. Wear dosimeters (e.g., film or TLD badges) if issued.

c. Avoid contact with the contamination.

d. Wash with nonabrasive soap and water, any part of the body that may have in contact with the contamination.

e. Assume that all materials, equipments, and personnel that came in contact with the contamination are contaminated. Radiological monitoring is recommended before leaving the scene

1.7 Units of Radiation

1.7.1 Activity

The activity of a radioactive source is the number of nuclei that decay in unit time. The unit of activity is the Becquerel (Bq) equal to one nuclear transformation per second.

1 Curie (Ci) = 3.7×10^{10} Bq

1.7.2 Absorbed Dose

It is the quantity of energy imparted to unit mass of material by ionizing radiation. The unit of absorbed dose is Gray (Gy Sv) equal to one joule per kilogram.

1 Gy = 1 J/kg

1.7.3 Dose Equivalent

The dose equivalent is the product of absorbed dose and the quality factor for a specific type of radiation. The quality factor accounts for the ability of the radiation to cause biological damage. For beta particles, gamma rays and x-rays the quality factor is usually taken as unity (1) but for alpha particles it is twenty (20). The unit of dose equivalent is Sievert (Sv) equal to one joule per kilogram.

1 Sv = 100 rems

1.7.4 Effective Dose Equivalent

This is the sum of the products obtained by multiplying the dose equivalent to various organs and tissues by the appropriate risk weighing factor for each. This quantity is also expressed in Sieverts.

1.7.5 Potential Alpha Energy

The potential alpha energy of an atom in the radon or thoron decay scheme is the total alpha energy emitted during the decay of this atom along the decay chain down to Pb-210 or Pb-208 respectively. For example in the case of Pb-208 it is 13.86 MeV (i.e. 6.00 + 7.86). It is usually expressed in J or MeV.

1.7.6 Potential Alpha Energy Concentration (PAEC)

Potential Alpha Energy Concentration (PAEC) in air of any mixture of radon and thoron daughters is the sum of the potential alpha energy of all the daughter atoms present per unit volume of air. It is usually expressed in J/m^3.

1.7.7 Working Level (WL)

One Working level (radon) is corresponding to a PAEC of short lived radon daughters in equilibrium with a radon air activity concentration of 3700 Bq/m^3 (100 pCi/l). It represents a concentration of radon-222 daughters which will deliver 2.08 x 10^{-5} J/m^3 (or1.3 x 10^5 Mev/l) of air in decaying through Po-214 (RaC').

1 Working level (thoron) is corresponding to a PAEC of short lived thoron daughters in equilibrium with a thoron air activity concentration of 275 Bq/m^3 (7.43 pCi/l). It represents a concentration of ThB (Po-212) and ThC (Bi-212) which yields 1.3 x 10^5 Mev/l of air in decaying through ThD (Pb-208).

1.7.8 Potential Alpha Energy Exposure

The Potential Alpha Energy Exposure represent the time integral of the potential alpha energy concentration (PAEC) of radon products in air to which the individual is exposed over a given time period. Its basic unit is $J.h/m^3$ but it often expressed in unit of Working Level Month (WLM).

1.7.9 Working Level Month (WLM)

The Working Level Month (WLM) corresponds to an exposure of 1 WL (2.8 x 10^{-5} J/m^3) during the working period of one month (170 hours).

1 WLM = 3.5 x 10^{-3} J h/m^3 = 22.1 x 10^6 MeV h/l

1.7.10 Equilibrium Equivalent Radon Concentration (EER)

The Equilibrium Equivalent Radon Concentration (EER) is the concentration of radon for which the daughters (if they were in equilibrium with it) would have the same potential alpha energy as the actual mixture of daughters has in the atmosphere of interest. In literature, the equilibrium equivalent radon concentration is also denoted by EEC and EC_{Rn}.

1.7.11 Equilibrium Factor (F)

The Equilibrium Factor (F) with respect to potential alpha energy is defined as the ratio of the Equilibrium Equivalent Radon (EER) to the actual activity concentration of radon in air.

1.7.12 Unattached Fraction of Potential Alpha Energy (f_p)

This is the fraction of airborne radon daughters that is not attached to aerosol particles, expressed in terms of potential alpha energy of the mixture and not in terms of the activity of any individual daughters nuclide.

1.8 Radon

Radon is one of the decay products of the uranium (^{238}U) and thorium (^{232}Th) decay series (figure 1.2) and was discovered by Ernst Dorn in 1900, who named it "Radium Emanation Gas". It was later named as radon in early 1920s. The atomic number of radon is 86 and like any

other noble gas, it is colorless, odorless and tasteless. It is eight times heavier than air with 33 known isotopes. Three of its isotopes i.e. ^{219}Rn ^{220}Rn and ^{222}Rn are naturally occurring and originate from natural radioactivity. The isotopes radon (^{222}Rn) and thoron (^{220}Rn), with half-lives of 3.84 days and 55.6 seconds respectively, constitute the major part of the gas's abundance [Ahad, 2004]. For humans, the greatest importance among radon isotopes is attributed to ^{222}Rn because it is the longest lived isotope of the three naturally produced isotopes [Durrani and Iliç, 1997]. It is well known that airborne short-lived radon and thoron progeny inhalation has a large contribution towards the radiation exposure of the public [UNSCEAR, 2000; NRC, 1999]. Radon is non reactive towards chemical agents. It is the heaviest member of the rare gas group i.e. ~100 times heavier than hydrogen and ~7.5 times heavier than air.

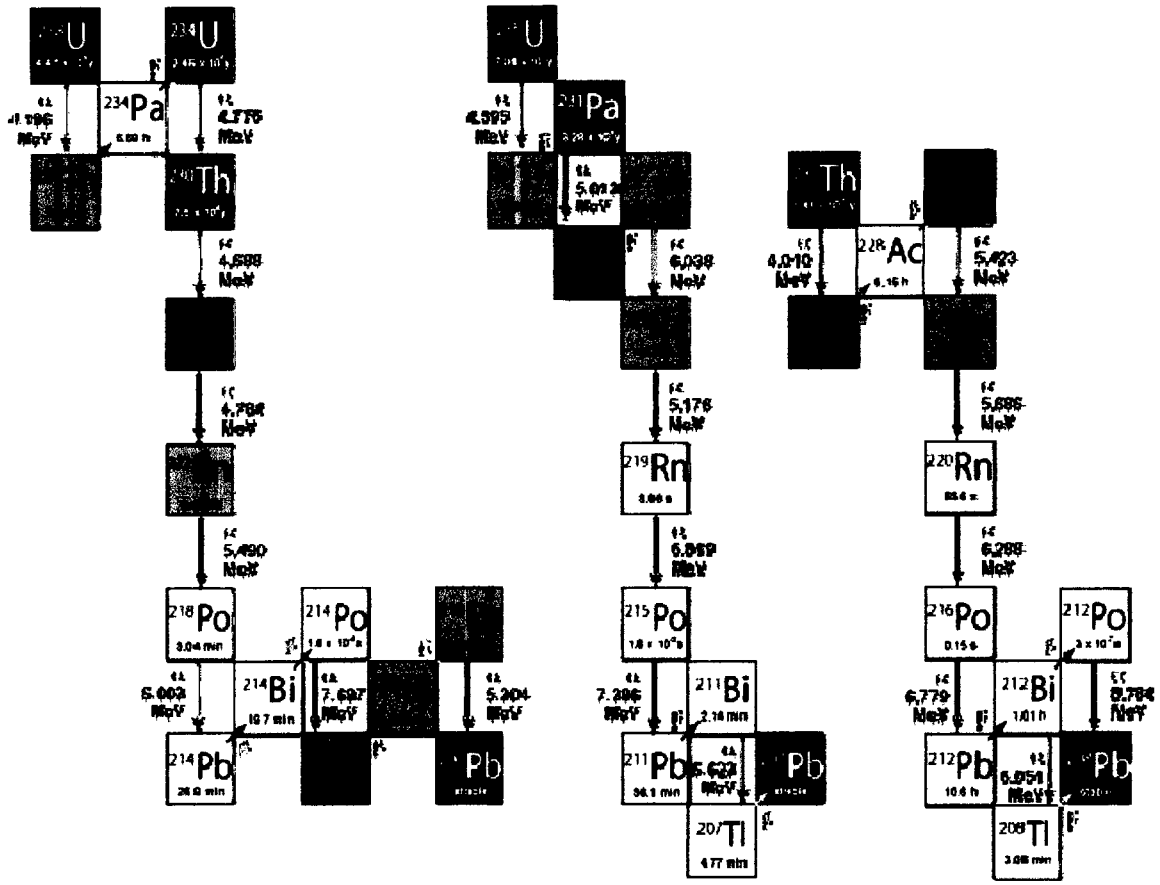

Figure 1.2 ^{238}U, ^{235}U, and ^{232}Th decay series

Being a noble gas, it has greater ability to migrate freely through soil, air, etc. [Verma et al., 2012]. The gas easily travels over significant distances, despite its short half-life. These unique characteristics make it an excellent marker for environmental changes, such as hydro-geological mixing and seismic activities in the ground. The health hazards due to inhaled aerosols with attached radioactive radon progeny account for as much as 50% of the risks associated with natural radioactivity [BEIR, 1999]. Radon emanates naturally from the ground and from some building materials all over the world, where traces of uranium or thorium can be found, and particularly in regions where soils containing granite or shale, which have a higher concentration of uranium. In fact, every square mile of surface soil, to a depth of 6 inches (2.6 km^2 to a depth of 15 cm), contains approximately 1 gram of radium, which releases radon in small amounts to the atmosphere [EPA, 1990]. In atmosphere the radon concentration is very low due to which radon-rich water exposed to air continually loses radon by volatilization. The ground water has generally higher concentrations of ^{222}Rn than surface water, because the radon is continuously produced by radioactive decay of ^{226}Ra present in the rocks. Radon is also found in some petroleum products. In oil refineries petrochemicals separate out based on their boiling points. In these oil refineries the pipes carrying freshly separated propane can become partially radioactive due to radon decay particles because radon has a similar pressure and temperature curve as propane. Residues from oil and gas industry often contains radium and its daughters. The sulfate scale from an oil well can be radium rich, while the water, oil, and gas from a well often contains radon. The radon decays to form solid radioisotopes which form coatings on the inside of pipe work. In an oil processing plant, the area of the plant where propane is processed is often one of the most contaminated areas, because radon has a similar boiling point as propane [NEB, 1994]. Some physical and chemical properties of radon shown in table 1.4.

1.9 Thoron

Thorium (^{232}Th) is the ultimate progenitor of thoron (^{220}Rn). Thoron was discovered in 1899 by R.B. Owens in collaboration with Ernest Rutherford at McGill University. Scientist gives the attention toward the thoron research after knowing that the thoron and its progeny is a major source of atmospheric ions near the earth's surface. These ions are responsible for a number of atmospheric processes which are necessary for radon and the formation of thunderstorm [Ramachandran, 2010]. Thoron and its progeny have also been used as tracer in the study of atmospheric transport processes, such as eddy diffusion. Much of these early atmospheric research was done by Israel and others [Israel et al., 1968; Israel, 1972] and the field has continued to be very active [Burchfiel,d, 1983]. The properties of thoron shown in table 1.5. In contrast, data on thoron is scarce due to the general perception that its level is negligible due to its shorter half life (55 sec), and its contribution to inhalation dose is ignored, in the presence of other more significant natural radiation. This may not be true from the recent studies resulted from the observation of high ^{220}Rn in the living environments of various countries and it is now increasingly felt that it may be necessary to have information on ^{220}Rn levels in the environment for obtaining a complete picture of inhalation dose. Radiation exposure due to inhalation of thoron progeny is estimated to be of the order of 10 ± 20% compared with short-lived radon progeny [Nambi, 1994]. Indeed, the decay products of 222Rn are the main radiation source, the dose emanating from decay products of 220Rn cannot be neglected since in some cases its progeny 212Pb (table 1.6) with a half-life of 10.6 h can accumulate to significant levels in breathable air [Kochowska et al., 2009]. Recent studies have shown that in some regions the exposure to 220Rn and its progeny can equal or even more than that of 222Rn and its progenies [Deka et al, 2009].

Table 1.4 *Physical and chemical properties of radon [UNSCEAR, 1982; Nussabaum, 1957]*

Properties	**Values**		
Boiling point	-61.8^0C		
Melting point	-71.0^0C		
Critical temperature	104^0C		
Critical pressure	62 atmosphere		
Density at normal temperature and pressure	$9.96\ Kg/m^3$		
Volume of 27.03 pCi at normal temperature	$1.6 \times 10^{-20}\ m^3$		
Vapour pressure at			
-144.0^0C	0.13 kPa		
-126.3^0C	1.3 kPa		
-111.3^0C	5.2 kPa		
-99.0^0C	13 kPa		
-71.0^0C	53 kPa		
-61.8^0C	100 kPa		
Coefficient of solubility at atmospheric pressure in water at			
0^0C	0.507		
10^0C	0.340		
20^0C	0.250		
30^0C	0.195		
37^0C	0.167		
50^0C	0.138		
75^0C	0.114		
100^0C	0.106		
Coefficient of solubility in	at 37^0C	at 18^0C	at 0^0C
Absolute alcohol	-	6.17	8.29
Acetone	-	6.30	7.99
Amyl alcohol	-	10.6	-

Aniline	-	3.80	4.45
Animal fats	5.5-6.5	-	-
Benzene	-	12.82	-
Carbon disulphide	-	23.14	33.4
Chloroform	-	15.08	20.5
Ether	-	15.08	20.09
Fatty acid	3.6-7.3	-	-
Ethyl acetate	-	7.35	9.41
Formic acid	0.96	-	-
Glycerin	-	0.21	-
Hexane	-	16.56	23.4
Human blood	0.43	-	-
Human fat	6.33	-	-
Linoloic acid	6.3	-	-
Oleic acid	6.7	-	-
Olive acid	-	29.0	-
Petroleum (liquid paraffin)	-	9.20	12.6
Toluene	-	13.24	18.4
Xylene	-	12.75	-

Table 1.5 Properties of thoron (^{220}Rn)

Properties	Values
Boiling point	-61.8^0C
Melting point	-71^0C
Solubility in water at	
0^0C	0.51
20^0C	0.25
50^0C	0.14
Solubility in Acetone at 0^0C	8.0
Diffusion coefficient in air at STP	0.1 cm^2/s
Diffusion coefficient in water at 18^0C	$\times 10^{-5}$ cm^2/s

Table 1.6 Decay series of thoron (^{220}Rn)

Series	Element	Traditional name	Half life	Radiation	α-energy (MeV)
232Th	220Rn	Thoron	55.6 sec	α	6.29
	216Po	Thorium A	0.15 sec	α	6.28
	212Pb	Thorium B	10.64 h	β	
	212Bi	Thorium C	60.55 min	{β (66.3%) to (212Po), α (33.7%) to (208Tl)}	6.1
	212Po	Thorium C	0.3 μsec	α	8.78
	208Tl	Thorium C'	3.05 min	β, γ	
	208Pb	Thorium D	stable		

1.10 Radon in Dwellings

In the early research work carried out on the indoor radon measurement it was found that the radon level in dwellings was generally low, however the highest indoor radon levels found in those dwellings which were close to the high radium activity source. Radium rich soil and building materials (mainly have uranium mill tailings) were considered to be the major sources and radon from these sources was believed to diffuse to the houses because of the permanent high concentration gradient. Now the discovering of higher indoor radon levels in dwellings built on rock or soil with normal level of radium and also had not the uranium mill tailings used in the building materials led to the search for the other entry processes [Scott, 1988; Scott, 1994; Rogers and Nielson, 1993]. Detailed studies shown that the radon gas in the soil flows into a structure primary through cracks, gaps, holes and other penetrations through the building's foundation. Figure 1.3 shows the entry routes of soil gas into a dwelling. Now days it is firmly believed that the higher entry rates of radon into dwellings occur through pressure driven flow processes. The air pressure inside the dwelling is usually lower than in the soil surrounding the foundation. This pressure difference within the dwelling drawing radon gas inside through foundation cracks and other openings. Furnace and air conditioning systems distribute the air through the structure. Radon may also be present in well water and can be released into the air in dwelling when water is used for showering and other household uses.

1.11 Sources of Indoor Radon

The sources of radon include the materials containing radium content such as soil, rocks, mining ores etc., and the materials carrying radon such as water, natural gas etc. In addition to these primary sources, there are some other factors that affect the indoor radon transportation such as the dwelling engineering (which include crawl spaces, sanitary fittings, etc.) and the meteorological parameters (such as temperature, pressure, etc.).

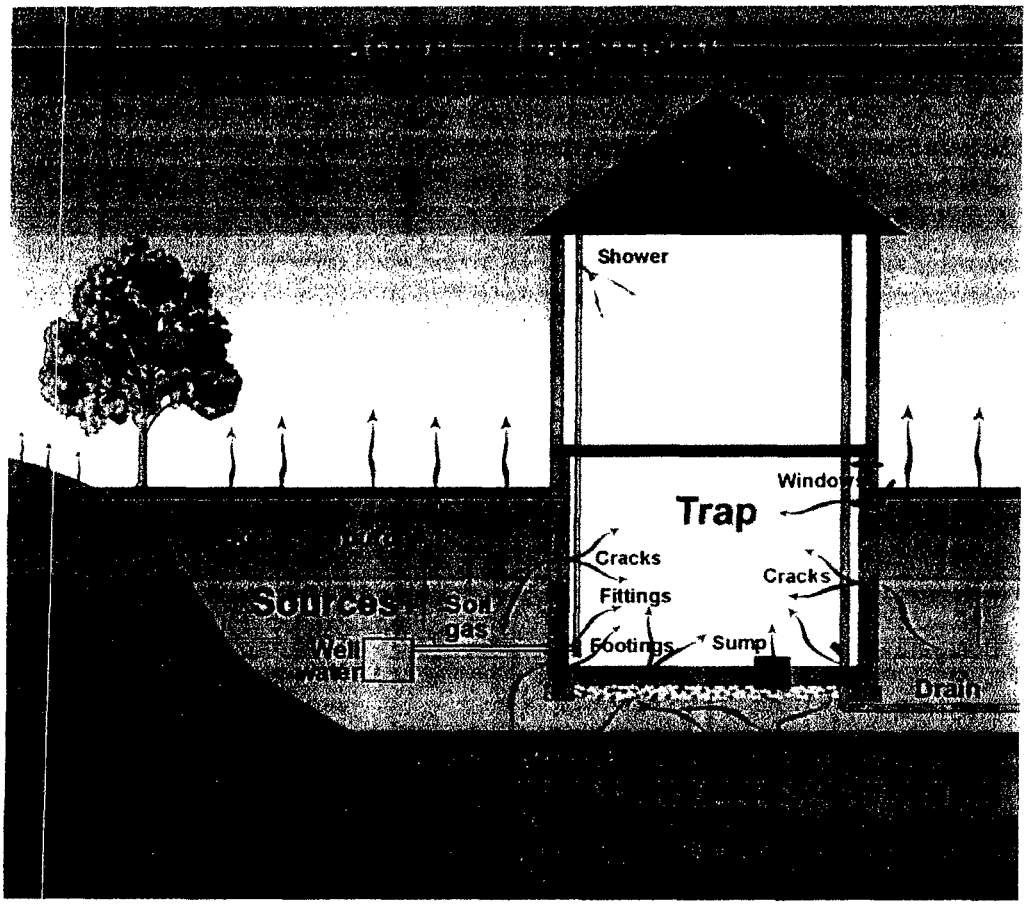

Figure 1.3 Radon entry points in a dwelling

1.11.1 Soil

Soil is the main source of continuous radiation exposure to the human beings. It acts as a medium of migration for the transfer of radio-nuclides in the environment; hence, soil is the basic indicator of radiological contamination. The naturally occurring radio-nuclides present in the soil are mainly ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K. Radon and thoron is constantly produced in soil and rocks from uranium and thorium series. The radon emanation rate in soil affected by many factors which include, soil moisture and porosity, radon concentration and their distribution, atmospheric and soil temperature as well as atmospheric pressure etc. At a higher atmospheric pressure the air is forced down by pressure gradient that forced the radon into the soil [Ferry et al, 2001]. Whereas at low pressure, the air in soil along with the radon is exhaled into the atmosphere from where radon gets entry into the buildings. In addition, a building situated on the ground acts like a chimney, drawing soil gas into itself from beyond its own perimeter as well as from beneath [Ahad, 2004; Nazaroff and Nero, 1988]. At least 80% of the global average radon entering into the atmosphere comes from the top layer of ground [NCRP, 1984]. The diffusion length for ^{222}Rn i.e. the average distance an atom can move through dry soil before decaying is about 1.6 meters while it is only 2 cm for thoron due to its relatively small half life of 55.6 s [Ahad, 2004; Muller, 1988]. Therefore ^{220}Rn is of less significance as far as its migration and diffusion is concerned. This is what makes radon a greater health hazard. Due to recoil of radon atoms and decay of radium, radon enters the air filled pores in the soil [Meggit, 1983]. The fraction of radon formed in the soil which enters the pores is called emanating power. The radon emanation rate from the earth's surface is about 0.5 pCi per m^2/s (0.0185 $Bq/m^2.s$) which corresponds to 160 Ci (5.92×10^{12} Bq) of radon per km^2 per sec. It is reported that about 10% of the radon is outflow into the atmosphere from soil; hence the annual amount of radon outflow from the total

land area (1.5 x 10^8 km^2) is about 7.57 x 10^{16} Ci [NCRP, 1984]. The emanation rate varies with radium concentration in the soil and soil permeability. In soil the area exhalation rate of radon varies from 0.0002 to 0.07 $Bq/m^2.s$ [UNSCEAR, 1988].

1.11.2 Building Materials

The building materials like bricks, concrete, sand, cement etc., containing uranium and thorium in varying amounts are the biggest inescapable source of natural ionizing radiation for human exposure. ^{222}Rn is the main isotopes of radon emanating from the building materials. There are several building materials made from soil and rocks used for the construction of the dwellings. These building materials contain several radionuclides presents in the earth's crust. They are one of the major sources of indoor radon concentration in dwellings. The building materials having radium (^{226}Ra) content more than 37 Bq/kg are especially the source of radon [Walsh and Lowder, 1993]. The industrial products having higher radium content are also used for the preparation of building materials [Stranden, 1983] therefore they are also the source of radon. Amount of radium present in different building materials in various countries shown in table 1.7. Only a small friction of the total radon activity produced by the decay of radium in building structure diffuse to wall surface and is released to indoor air. This friction strongly depends on the emanating power and porosity of building materials as well as bulk diffusion coefficient of radon in them. The radon emanation rate is influenced by the type of the materials and the environmental conditions.

Owing to the influence of these parameters the rate of radon entry from building material cannot be predicted by measuring the radium content alone. However rate of radon can be estimated from exhalation rates which have been measured for different building materials [Azam, 2002]. Several Survey have been carried out to measure the radium content and radon exhalation rates from building materials [Paschoa, 2000; Beretk

Table 1.7 Radium (^{226}Ra) content of different building materials in different countries [Azam, 2002; Ramachandran T. V. and Subba Ramu, 1989]

Material	Country	Average activity content of ^{226}Ra (Bq/kg)
Brick	Norway	104.0
	UK	52.0
	USSR	55.5
	W. Germany	59.0
	Finland	778.0
	India	48.1
Cement	Norway	30.0
	UK	22.0
	USSR	25.9
	W. Germany	25.9
	Finland	44.4
	India	86.0
Concrete	USSR	14.8
	W. Germany	104.0
	UK	89.0
	India	30.0
Sand (Gravel)	UK	7.4
	Finland	37.0
	India	1850.0

and Matthew, 1985; Zikovsky and Kennedy, 1992; Tahir et al., 2005; Durrani and Iliç, 1997]. The radon emanation rate within the building materials vary substantially from one sample to another even if radium content is approximately same. The physical properties such as atmospheric pressure and humidity account for the wide dispersion of escape to production rate.

Recently, the use of granite, marble and ceramic is increased in the decoration of old and new dwellings. The sources of this type of construction materials are local, regional and international. Radon exhalation from construction materials varies with their type and origin. In general granite exhale more radon than other types of construction material due to the presence of relatively high uranium content in its natural form [Durrani and Iliç, 1997]. However it is always possible to find uranium-rich bedrocks of different types as construction materials [Bertrand et al., 1994]. The Knowledge of total internal surface area of construction material and radon exhalation rate from the surface will enable the estimation of indoor radon levels from the construction materials to the indoor air.

1.11.3 Ground Water

After soil, the ground water is considered to be the next most important source of radon. When ground water comes into contact with radium/radon bearing soil and rocks, they dissolved and transported with the water. When this ground water reaches to the surface, most of the radon released to the environment but small amount left in the water which correspond to a large amount of radioactivity [Bodensky, 1987]. The amount of radium and uranium content in groundwater increases the radon risk. The adverse health effect of radon in water is mainly due to the transfer of radon to the air, where it decays and its short lived radioactive daughters inhaled by human being. The water supplies may be classified into surface water, ground water and well water. As shown in table 1.8, the

concentration of radon in three types of water supplies differs by an order of magnitudes and utilization [Nazaroff, 1988]. It is evident from table 1.8 that waterborne radon poses a problem for those houses that use well water. For houses that use water from the public utility system, waterborne radon does not contribute significantly to the radon level in indoor air. The concentration of radon in water depends upon the type of the host rock. The occurrence of radon in water is controlled by the concentration of radium in the host soil or rock and the emissivity of radon in water. The physical condition such as grain size distribution, porosity, etc. of the rock matrix appears to play a greater role in radon release into water than does the concentration of radium [Hess et al, 1985]. The global value of radon concentration in water ranges from 500 pCi/l to 170,000 pCi/l [UNSCEAR, 1993]. However, despite this very high level of radon, ground water is responsible only a small fraction (1 to 7%) of radon emitted into the atmosphere. The upper limit for the global concentration is estimated to be 5 x 10^8 Ci/y, or about one fifth the amounts released from the soil [Bodensky et al., 1987]. A large amount of radon can exist in the water even at temperature more than the boiling point of water.

1.11.4 Outdoor Air

In a dwelling the outside air enters through open doors, windows, ventilators and it brings within radon usually at a low rate. In environment the radon concentration depends on the radon exhalation from the earth and the meteorological conditions like temperature, humidity, pressure etc.. The radon concentration level has shown diurnal and seasonal variations. The specific entry rate $R_{n(i)}$ of radon from outdoor air into dwellings due to ventilation is given by the relation

$$R_{n(i)} = \lambda_v R_{n(o)}$$

Where $R_{n(o)}$ is the radon concentration in outdoor air and λ_v is the air exchange rate constant between outdoor and indoor air.

Table 1.8 Concentration of radon in three types of water supplies

Types of supply	Radon concentration Bq/m^3			Utilization (%)		
	US	UK	Reference value	US	UK	Reference value
Surface water	1100	1000	1000	49.5	66	60
Ground water	11500	30000	10000	32.2	34	30
Well water	208000	<1000000	100000	18.3	<1	10

1.11.5 Natural Gas

Radon emanates from the porous geological formations and mixed with the natural gas, then it moves along with the natural gas to the point of their use such as kitchen and room heating [Ahad, 2004]. The concentration of radon at wells has been measured from undetectable limit up to about 5.4×10^4 Bq/m^3. The concentration of radon at the place of its use depend upon the factors such as the concentration of the radon at the well head, production rate of natural gas, natural gas processing, pipeline dilution, pipeline transmission time, and storage time [Muller, 1988]. In natural gas the radon concentration is ranges from 0.1- 0.2 pCi/l which is much less than from other sources. On an overall basis, natural gas is not a significant contributor to indoor radon [Bodensky et al., 1987]. Table 1.9 presenting the values of the radon entry rates from the various sources for a modal masonry building in temperature climate. In liquid petroleum gas (LPG) radon is also transferred and its concentration in LPG range from 70.3 to 4.8×10^4 Bq/m^3 [Johnson et al., 1973].

1.11.6 Uranium Mill Tailing

The residue remains after the extraction of uranium from the ore is known as tailing. It contains virtually all mass of the ore and a considerable amount of radioactivity due to radionuclides of uranium decay series. The tailing increases about 8% of average radon emission from the surface [NCRP, 1984]. In many places tailing has been used to fill in building construction [Guimond et al., 1979]. At these places specific activities and radon concentration have been found several times more than the permissible levels.

1.11.7 Non-Uranium Mining

The higher concentration of radium/radon is also found in some non uranium mining ore. In phosphate mines, the phosphate ores have a relatively high concentration of radium (about 1500 Bq/m^3) [Roessler et al., 1983], which is about 50 times more than

Table 1.9 Radon entry rates for a model masonry building in temperature climate [UNSCEAR, 1993]

Sources of radon	Mechanism	Entry rate ($Bq/m^3.h$)	Percentage (%)
Building elements	Diffusion	10	21
Subjacent earth	Diffusion	7.5	15
	Advection	20	41
Outdoor air	Infiltration	10	20
Water supply	De-emanation	01	02
Natural gas	Consumption	0.3	07
All sources		49	100

the average concentration of radium in an ordinary soil. Also the dwellings situated on the land filled with mining residue shown the higher concentration level of radon.

1.11.8 Dwelling Design

The dwelling engineering plays an important role in order to decide the indoor radon level. There are several points from which air leaks into a dwelling like cracks and interstices, ceiling, floor, and walls of a dwelling and through sanitary fittings [Johnson, 2000]. This process is known as infiltration. Building shape and its orientation to the wind direction also influence the distribution of wind pressure, which cause infiltration. Tightness of construction will affect the location and degree of infiltration. The location of doors, windows, and other internal openings not only affects the infiltration, but also determines where natural and forced ventilation may occur. The installation of fans in dwellings influences the degree of air exchange by mechanical ventilation. Building height also becomes important due to buoyancy of warm air where indoor radon concentration generally decreases from the base of the first floor and from the first floor to the higher floors for the time of normal activity. However, other situations have been described which involve the chimney and stack effects, where radon concentration on the first or second floor is higher than in the basements [NCRP, 1984]. It has been concluded that infiltration of soil gas directly into a dwelling is generally the greatest contribution to indoor levels. Air gaps found under foundations are an effective conduit for channeling the radon flux beneath a house to a few cracks in the foundation. Whereas cracks in the concrete basement walls or basement slaps are the most common source of radon diffusion in such dwelling. The joints between the walls and floor is the next common pathway. Other sources are loose fitting pipes through walls or floors drains connected to weeping tiles, providing a direct pathway into the basements.

1.11.9 Occupant Life Style

Occupant Life Style affected the indoor radon concentration in several ways. The dweller activities such as opening and closing of doors and window, use of fans, air condition etc. affect the indoor outdoor air exchange rate which causes variations in radon level inside the dwellings. The location and operation of fans affect the ventilation. Radon concentration varies with the use of natural gas which depends upon its use in winter or summer season, the place and duration of its use in the dwelling [Muller, 1988]. The amount of radon in the air due to use of water depends upon amount, time and place of water used.

1.11.10 Meteorological Parameters

The natural radioactive noble gas radon is constantly evolving in the geological subsoil. It is partially released into the air-filled pore spaces of rocks and soils. From the subsoil, radon reaches outside air and enters dwellings. The indoor radon concentration is affected by exhalation rate and infiltration due to the meteorological changes such as moisture, temperature, wind and atmospheric pressure. The following is the brief description of the meteorological parameters, which influence the indoor radon concentration.

1.11.10.1 Pressure

Barometric pressure changes have been found to cause significant changes in radon concentrations. A sudden drop in the pressure tends to draw soil gas out of the ground, increasing the radon concentration in the near-surface layers. Whereas high or increasing barometric pressure forces atmospheric air into the soil, decreasing the radon concentration [Janssens et al., 1989]. The radon flux from soil [Clements and Wilkening, 1974] and the concentration in soil gas [Kraner, 1964] have been observed to change inversely with changes in barometric pressure. A good agreement has been found

[Clements and Wilkening, 1974] between a theoretical model, which combine flow and diffusion effects during pressure changes, and experimental results.

1.11.10.2 Temperature Differences

Temperature differences between the indoors and the outdoors can cause air volume movements corresponding to the temperature gradient and, consequently, pressure differences. Low outdoor air temperature leads to a negative pressure difference between the building and the outdoor atmosphere. As the air temperature indoor is higher than outdoors, therefore there is an upward movement of air in the building. Warm air flows away from the building (exfiltration) through the open windows and cracks. To equalize pressure the outdoor air enters the building (infiltration). The pressure differences also vary with the wall height. This phenomenon is known as the stack effect [Nero, A. V. and Nazaroff, 1984]. The radon concentration in the outdoor atmosphere as well in the indoor air also represents daily variations, which are closely connected to the temperature, i.e., with the solar heating of the earth's surface.

1.11.10.3 Wind Speed

The radon emanation increases linearly with increase in wind speed. However for the very low wind speeds generally observed between the grass blades at 1.25 cm above the ground, there is no demonstrable variation of radon emanation with variation in wind speed [Nero, A. V. and Nazaroff, 1984]. The wind drives radon from the soil due to exchange of air between the dwelling and soil. The details, how wind speed varies with height near the ground is important in characterizing how radon entry depends on this factor [Pearson, 1967].

1.11.10.4 Moisture

The moisture content has a large impact on the emanation coefficient and on the soil transport parameters for radon gas and thus affect the radon concentration in soil.

Pearson observed a significant variation of emanation coefficient with soil moisture over a time period of days to weeks [Pearson, 1967]. There seem to be three major effects of moisture causing an increase in radon exhalation [Straden. 1984]: a. the direct recoil fraction of the emanation power is increased when there is fluid present in the internal pores of the materials, b. the fluid may hinder absorption of radon gas on internal pores of the materials, and c. if there is a moisture content gradient in the sample, active transport of radon on water molecules may take place. If the porosity of the sample is high, more water will be taken up by the sample before the pores are filled and a large amount of radon exhalation will occur due to higher moisture content [Straden. 1984].

1.12 Hazard from Radon Exposure

The health hazard associated to radon and its daughters have become a matter of great public concern. It has been established that radon and its daughters contribute about 68.8% of the dose received by humans from natural sources of radiation [Khan et al., 1990]. Most of the energy released by radon decay series is in the form of the alpha particles, which affects the humans both externally and internally.

1.12.1 External Radiation

The alpha particles emiited from radon and its progenies (table 1.10) have enough energy to penetrate into the tissue reach to the inner cell and damage the body tissue. A typical alpha particle of ejection energy 5.5 MeV can penetrate about 40 μm in soft tissue. This distance is equivalent to the length of four cells in the tissue. Alpha particle would have produced about 160,000 pairs of ions before it loses all of its energy. This is about 40,000 ion pair in one cell [NRC, 1981] compared to about 60 pairs produced by a 2 MeV beta particle. However the alpha particle needs 7.5 MeV of energy to penetrate our skin because the top layer of epidermis and keratin flakes formed by dead cells or cells without nuclei. From table 1.10, it is clear that only ^{214}Po (7.64 MeV) emit alpha

Table 1.10 Alpha (α) energy of radon and its progeny [Mahur, 2008]

Series	Element	Traditional name	Half life	Radiation	α-energy (MeV)
^{238}U	^{222}Rn	Radon	3.82 d	α	5.45
	^{218}Po	Radon A	3.05 min	α	6.00
	^{214}Pb	Radon B	26.8 min	β, γ	
	^{214}Bi	Radon C	19.8 min	β, γ	
	^{214}Po	Radon C'	164 μsec	α	7.69
	^{210}Pb	Radium D	22.3 years	β, γ	
	^{210}Bi	Radium E	5.1 days	β	
	^{210}Po	Radium F	138.4 days	α	5.30
	^{206}Pb	Radium G	Stable		

particle having sufficient energy to penetrate our skin. In uranium mines where radon levels are very high, ^{214}Po is suspected to be the cause of skin cancer among miners [Sevcova et al., 1978]. Being an effective ionizing agent an alpha particle also loses its energy readily in the air at a rate of about 1 MeV per cm. Thus our skin is impenetrable even to these energetic particles if the alpha emission takes place just a cm away from the skin surface.

1.12.2 Internal Radiation

Significant health hazards may result from inhalation and ingestion of alphas producing from the radon and its daughter product. This alpha particle enters into the human body mainly through inhalation. The principal health effect attributed to inhalation of radon and its daughters is lung cancer. Although radon is chemically inert and electrically uncharged but it is radioactive, which means that radon atoms in air can spontaneously decay, or change to other atoms. When the resulting atoms i.e. radon progeny, are formed, they are electrically charged and attach themselves to tiny dust particles in indoor air. These dust particles can easily be inhaled into the lung and can adhere to the lining of the lung. The deposited atoms decay, or change, by emitting a type of radiation called alpha radiation, which has the potential to damage cells in the lung. Alpha radiations can disrupt DNA of these lung cells. This DNA damage has the potential to be one step in a chain of events that can lead to cancer [William et al., 2000; Lubin and Boice, 1997]. The connection between radon and lung cancer in miners has raised the concern that radon in homes might be a cause of lung cancer to the general population, although the radon level in most homes is much lower than in most mines. The general population is exposed to much lower levels of radon progeny than the uranium miners. Uranium miners were also exposed to other materials including cigarette that could have influenced lung cancer induction. Other differences relate to work state

(i.e. breathing rate), nature of aerosol distribution and population characteristics such as age, sex and relative lung physiology. In addition, through ingestion and blood transport, following the crossing of the lung membrane by radon, radioactive progeny may also be transported to other parts of the body.

The average individual in the United States receives more radiation dose from exposure to indoor radon decay products than from any other source of natural or man-made radiation [UNSCEAR, 2000]. Occupational exposure to radon in uranium and other mines is a well documented cause of lung cancer [NRC, 1999; Lubin and Boice, 1997; Leuraud et al., 2007; Gilliland et al., 2000]. In addition, there is now direct evidence that prolonged radon exposure in homes represents a significant health risk. Both the North American as well as the European pooled studies supports the risk projections extrapolated from occupational studies of radon-exposed underground miners [NRC, 1999], and provide direct evidence that prolonged residential radon exposure represents a major cause (even below the U.S. EPA's action level of 4 pCi/l) of lung cancer. Empirical studies performed by Field et al. [Field et al., 2000] suggest that pooled risk estimates are likely underestimates of the true risks. Based on the studies of radon-exposed miners, the EPA estimates that approximately 21,000 radon-related lung cancer deaths occur each year in the United States [USEPA, 2003] making it one of the most significant public health risks in the United States [Johnson, 2000]. A few ecological and case control studies have indicated that exposure to indoor radon could be of some importance as a cause of other cancers, especially acute myeloid leukemia (AML), melanoma and kidney cancer, but the studies were not generally consistent with each other and most of them found no significant associations [Wolff, 1991; Eatough and Henshaw, 1993; Kaletsch et al., 1999; Evrard et al., 2005]. However, in a recent study, Rericha and colleagues [Rericha et al., 2006] examined the incidence of leukemia, lymphoma, and multiple

myeloma in Czech uranium miners. The investigators noted that exposure to radon and its progeny was positively associated with an increased risk of developing leukemia. A surprising result of the research was that Chronic Lymphocytic Leukemia (CLL), which was not previously believed to be radiogenic, was also positively associated with radon exposure. In addition, both myeloid leukemia and Hodgkin lymphoma were also positively associated with radon exposure. The latter findings regarding myeloid leukemia and hodgkin lymphoma were not statistically significant. Another recent study performed by Smith et al. [Smith et al., 2007], reported suggestive evidence of a positive association between county radon levels and both CLL and Chronic Myelogenous Leukemia (CML).

1.14. Action Level of Radon in Dwellings

Many countries have defined an action level of radon concentration to guide their program to control domestic radon exposure (table 1.11). The action level is not a boundary between safe and unsafe, but rather a level at which action on reduction of radon level will usually be justified. Some people may choose to take action when the action level is approached. For example, many countries consider indoor radon concentration of 200 Bq/ m^3 as an action level at which mitigation measures should be taken to reduce radon levels in dwellings. The United States set a maximum contaminant level of 150 Bq/l for radon concentration in drinking water from private water supplies. The European Union Commission recommended action level of 1000 Bq/l. This is set so that the risk to a typical person drinking such water is similar to the risk from breathing air which contains radon at the action level of 200 Bq/m^3. The domestic radon concentration and their action levels vary among countries (table 1.12).

Table 1.11 Indoor radon level recommended by different national and international agencies

Recommended level of radon (Bq/m^3)	Reference
150	USEPA (1986)
400 (for existing houses)	ICRP (1993)
250	FRG (1988)
200	NRBP (1990)
200-600 (for dwellings)	ICRP (1993)
500-1500 (for workers)	ICRP (1993)

Table 1.12 Domestic radon concentrations and Action Levels in different countries [UNSCEAR, 1993; UNSCEAR, 2000]

Country	Average radon concentration in homes (Bq/m^3)	Action level ($Bq/m^{3)}$
Czech Republic	140	200
Finland	123	400
Germany	50	250
Ireland	60	200
Israel	*	200
Lithuania	37	100
Luxembourg	*	250
Norway	51-60	200
Poland	*	400
Russia	19-250	*
Sweden	108	400
Switzerland	70	1000
United Kingdom	20	200
European Community	*	400
USA	46	150
Canada	*	800

1.15 Benefits of Radon

Apart from its harmful effects, radon has some useful applications. Radon's unique properties as a naturally radioactive gas have led to its use as a geophysical tracer for locating buried faults and geological structures, in exploring for uranium, and for predicting earthquakes. Radon has been used as a tracer in the study of atmospheric transport process. There have been several other applications of radon in meteorology, water research and medicine. Some of them are given below.

1.15.1 Geothermal Energy Prediction

A geothermal source may be defined as the natural heat of the earth trapped close enough to the earth's surface to be extracted economically. Normally, geothermal sources are associated with volcanic regions. Hot water springs and vapors emanation may suggest prospecting geothermal energy sources. The observation of exceptionally high radon levels may indicate the possible existence of a geothermal energy sources lying deep underneath the earth's surface. The method of using radon signal for locating geothermal energy sources has met some success in countries such as New Zealand, Mexico and USA [Durrani and Iliç, 1997].

1.15.2 Medical Application

It was first used medically in 1914 by Prof. John Jolyand W.C. Steveson [Steveson, 1914]. Using radon they treated several malignant and non-malignant conditions. Rather early, the stimulation of DNA repair was observed upon radon exposure. Similar DNA repair was indicated in lymphocytes of people living in increased radon concentration and also the adaptive response reaction were provoked under 10 mSv 'priming' dose [Durrani and Iliç, 1997; Masoomi et al., 2006]. The spas evidently containing radon have been used in USA, Japan and Europe for special illnesses mainly in the pain therapy of chronic rheumatic illnesses. Clinical experience has shown that the

long-lasting pain of the patients was considerably reduced with less analgetic pharmaceuticals. The presence of radon in spas, accordingly, cannot be considered as risky to health, just the opposite, more and more information cumulate on its positive health effects completing the other beneficial factors present in health spas [Durrani and Iliç, 1997; ICRP, 1993; Vagiannis et al., 2004; Vaupotic and Kobal, 2001].

1.15.3 Earthquake Prediction

Radon is constantly generated all over the earth due to the decay of radium present in the earth. Radon concentration in soil gas and in ground water has been observed to change markedly prior to or during an earthquake and volcanic eruption. This anomalous behavior of radon concentration can be used for earthquake prediction. On the basis of some studies carried out in hot springs in Japan, Shiratoi in 1927 suggested that a correlation might exist between radon level variations in the ground and seismic phenomena [Bella, 1990]. Active faults having high radon levels were located in the Massif Centarl France during the mid thirties [Monin and Seidal, 1991]. In 1944, Hatuda who measured the radon content in soil gases near active faults observed an anomalous changes before Tanankai earthquake (M=8.0). Since then anomalous radon changes in ground water and soil have been reported for a number of earthquakes at stations located several hundred kilometers from their epicenter [Sadvosky et al., 1972].

1.15.4 Seed Application

Radon seeds were used as an adjunct to surgery of certain oral and nasopharyngeal tumors [Hileris, et al, 1976; Beheshiti and jawed, 1978]. Radon seeds can be left in situ because of their short half life. Since radon emits no gamma rays so it is not directly the source of radiation. Its progeny ^{214}Pb and ^{214}Bi, supply most of the gamma radiation. However, other reasons such as cost availability and practicality, other

radionuclides such as Cobalt-60, Cesium-70, Tantalum-182, Iridium-192 and Gold-198 are preferred [Hileris, et al, 1976; Landa, 1982a].

1.15.5 Uranium Exploration

Radon is a member of the ^{238}U decay chain so it can be used for the uranium exploration [Tanner, 1980; Card, 1985]. Alpha sensitive plastic detectors are used to search large area of lands for sites of high radon concentration in the soil [Weidenbaum, 1970b; Gingrich and Loyett, 1972] as described in detail by Gingrich [Gingrich, 1973]. Such sites are then recognized as desirable locations for exploratory drilling by substance ore.

1.15.6 Oil Exploration

Radon gas travels deep into earth's crust and is trapped by fluids such as oil [97-99]. It migrates due to different types of fluid movements and under favorable circumstances; it is brought to the earth's surface [Donovan, 1974; Donovan, 1977; Fleischer and Turne, 1984]. A number of experiments were carried out in USA for finding the correlation between radon anomalies and the oil deposits. Investigations, based on measurements carried out over a period of two months or so in Oklohoma (USA) indicated a strong correlation between the oil reserves and the intensity of radon signals [Donovan, 1974]. Similar results have been reported at some other sites of the USA. More work is required to be carried out for making the correlation between the radon emanation and the amounts of hydrocarbon deposits [Fleischer, 1988].

1.15.7 Other Used

The distribution of concentration of radon in ground water reflects the vertical and horizontal hydro geological structure [Kimura and Komae, 1980]. Large discontinuities have been observed in radon concentration at the air-sea and sea sediment interface.

These measurements have led to a better understanding of ocean circulation [Broecker, 1965].

Motivation

Radon-222 is a naturally occurring radioactive gas that is part of the Uranium decay series. It is present in the environment associated mainly with trace amounts of uranium and its immediate parent, radium-226, in rocks, soil and groundwater. About one-half of the effective doses from natural sources are estimated to delivered by inhalation of the short lived radon progeny [UNSCEAR, 2000]. Radon is cited as the second leading cause of lung cancer after cigarette smoking. Owing to this fact, radon is the most popular subject of studies on environmental radioactivity. The presence of high levels of radon in indoor environment constitutes a major health hazard for the general population. The radon progeny is a well established causative agent of lung cancer and other types of cancers [Lubin and Boice, 1997]. Statistics indicate that radon gas that appear from the cracked buildings affected the health of human. Keeping in view of the detrimental effect of radon and its progeny, their measurement in the dwelling has become very important from the health hazard point of view. Nationwide surveys have been carried out in many developed countries to find radon levels in different dwellings [Nazaroff and Nero, 1988; Meggit, 1983; Field and Becker, 2001; Evrard et al., 2005]. In India too, there have been a plea for a national effort on monitoring of indoor radon [Subba Ramu, 1991; Khan et al., 1988; Khan et al., 2011; Verma et al., 2012].

In light of the above facts, we have studied the radon, thoron and their progeny in indoor and outdoor environment and we have measured these parameters in different Indian cities i.e. Farrukhabad, Faizabad and Bareilly. We have also estimate effective dose, lifetime fatality risk and annual exposure to the population of the study area. Besides that, we have measured the values of radium content and radon exhalation rates in soil of

different study area. Our results have been found good agreement with the results reported by other researchers in neghbouring areas. Almost all the above said parameters found under the safe limits recomended by various radiation protection agencies like UNSCEAR, ICRP, EPA etc.

It is expected that the results obtained from present work will be useful for various radiation protection agencies for ensuring the safety measurements against the possible radiation health hazard caused by radon/thoron and their progeny to the general population of this region of India. It will also be beneficial to people of study area in order to understand more about the radon and their effect to human health.

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CHAPTER-II

MATERIALS AND METHODS FOR RADON MEASUREMENT

After discussing the properties, transport and health effect of radon, the next step is the monitoring of radon. As mentioned earlier that radon convert to their progeny by emitting an alpha particle, therefore radon can be measured/detected either directly by radon itself also called radon alone measurement or indirectly though its daughters. Since radon and its progeny decay by emitting alpha (α), beta (β) and gamma (γ) radiations, therefore radon detection and measurement can be performed through the detection and measurement of these radiations.

2.1 Radon Measurement Techniques

Many techniques are available in the literature for the measurement of radon. They are classified into two main categories:

a. Instantaneous/active techniques

b. Time integrated/passive techniques

2.1.1 Active Techniques

These techniques require power for their operation and are used normally for short term measurements. They are based on the methods in which grab sample of the air is collected at an instant of time, followed by measurement of radon concentration through its α-particle activity. These techniques are briefly discussed under the following subsections.

2.1.1.1 Surface Barrier Detectors (SBD)

A surface barrier detector (SBD) is a semiconductor (p-n junction diode) detector operated under reversed biased conditions. The α-particles produce during the radon decay enter the depletion region and create electron hole pairs, which flow in opposite

directions. The total number of electrons collected can form an electric pulse whose amplitude is proportional to the energy of the radiation.

2.1.1.2 Two Filter Method

Two filter method is a historical device used for the measurements of both radon and its daughter's concentrations in air [Thomas and Leclare, 1970]. The two filter tube is a metal cylinder with a high efficiency filter at each end. In this method, air is passed through a tube of length about 0.3 to 1.0 m after filtered through first filter at the entrance so that radon daughters are removed. The filtered air is then pass through the length of tube so that the daughters grow again are collected on the second filter fixed at the exit point. Both the filters are removed and counted separately by the measurements of alpha decays. The second filter gives the radon concentration whereas the first filter gives radon daughter concentration.

2.1.1.3 Working Level Method

This method involves a filter through which a sample of air passed for a given time period. Alpha particles emitted from radon daughters deposited on the filter are counted by using SBD. A modern instrument 'Mensura Working Level Meter' can be used for this purpose. It works by sampling air from the environment at a constant rate. It is operated by a mobile battery power supply.

2.1.1.4 Scintillation Method (Lucas Cell)

Scintillation produced by the α-particles detected by the Lucas cell. This cell consists of glass vessel coated inside with scintillation materials such as ZnS, except for a clear window of quartz or glass and coupled to a photomultiplier tube (PMT). The cell is filled with a sample of air or other gases having radon, which decay by emitting the α-particles. The energy of α-particles converted into light pulses and these pulses are counted by a discriminator.

2.1.1.5 Ionization Chamber

Ionization Chamber is basically a capacitor of cylindrical shape, in which an electric field is established between two electrodes. When the air contains radon enter into the chamber, the α-particles emitted during the decay of radon will ionize the air and a current starts to flow between the electrodes. In the presence of applied voltage the electrons and ions are drifted toward their respective electrodes. The resulting current is a measure of the quantity of decayed radon atoms. Counting is started after the establishment of equilibrium between radon and its decay products and the radon concentration can be obtained from the number of pulses.

The above said active measurement techniques are not so beneficial to measure the accurate radon levels because of temporal variation in radon level due to the temperature and pressure gradients.

2.1.2 Passive Techniques

In order to see the combined effects of seasonal, weather and environmental conditions on radon concentrations in dwellings, it is very important to carry out the radon measurements over a long period of time. This long-term average in dwellings helps to determine the damage to human health. The use of passive techniques is the most practical way of obtaining long term average radon concentration. Hence these techniques are preferred to determine the annual average radon concentration. These techniques are briefly discussed here.

2.1.2.1 Charcoal Canister Technique

This technique is used for the monitoring of radon because the activated charcoal has a capacity for adsorbing and retaining radon. In this technique a canister containing activated charcoal is exposed for a few days (about 1 to 3 days), so that radon enter in the canister. The amount of radioactive material collected in the activated charcoal is

evaluated by gamma spectroscopy or by liquid scintillation counting. The problem with this technique is that it needs a sophisticated electronics for the analysis and secondly the results cannot be reproduced even in the same location for similar experimental conditions.

2.1.2.2 Thermoluminiscent Technique

Thermoluminiscense is the property by which certain substances are capable of storing energy that can be released in the form of light when they heated. These substances are known as Thermoluminescent Detectors (TLDs) chips. These TLDs are sensitive to α, β and γ radiation, a procedure has to be adopted for the alpha contribution only. Two TLDs are mounted in an inverted cup and placed in the ground. One of the TLDs is wrapped in a foil that will allow escaping all α-particles and contain only beta and gamma radiations. After a certain time the TLDs are retrieved and analyzed by heating up to 300^0C in an appropriate read out equipment. On heating a light is emitted from the chip which is proportional to the amount of radiation present. The contribution from alpha radiation can be determined by subtracting the intensity of the energy in first TLD (expose to only beta and gamma radiation) from second TLD (expose to alpha, beta and gamma radiation) which ultimately gives the amount of radon activity [Hussain, 1997].

2.1.2.3 Electrets

The Electrets are lightweight, inexpensive and suitable for indoor radon measurements. They contain an electro-statically charged teflon disk and are widely used for the long term measurement. Ion generated by the decay of radon strike and reduces the surface voltage of the teflon disk. By measuring the voltage reduction, the radon concentration can be calculated.

2.1.2.4 Etched Track Technique

The above said passive techniques require extensive electronics and sophisticated laboratory facilities which makes them unsuitable for use in distant and rugged areas. Also the instruments used in passive techniques are expensive and not easily available [Khan and Qureshi, 1994]. Recently the track etch technique [Alter and Fleischer, 1981; Fleischer and Mogro-Campero, 1978] based on materials known as Solid State Nuclear Track Detectors (SSNTDs)/etched track detectors, has been used for passive and time integrated measurements. It is the most widely used techniques to monitor low levels of radon in the indoor environment over long integrated times [Alter and Fleischer, 1981; Fleischer et al., 1980; Frank and Benton, 1977; Durrani, 1982; Ramolaet al., 1987]. This technique is simple to use and relatively inexpensive. Several detector materials have been developed but the most suitable SSNTDs for the radon measurements are LR-115 type-II and CR-39 because of their good sense and stability against environmental factor.

2.2 Solid State Nuclear Track Detectors

We have used the Solid State Nuclear Track Detectors (SSNTDs) to perform our experimental work. Due to their durability, simplicity and the specific nature of the response, SSNTDs are used in a wide variety of applications in many branches of science and technology. These applications include studies in nuclear physics, radiography, cosmic rays, dosimetry, environmental science, geosciences, indoor radon measurement, earth sciences, mineral exploration, etc. [Fleischer et al., 1975,].

The basic principle of track detectors is based on the fact that when a heavily ionizing charged particle passes through a solid insulator, it creates the microscopic trails of radial damage along their path. The latent tracks can be visualized by etching these trails. These particle tracks are formed only in insulating materials not in conductors or semiconductors. The classification of track storing and non track storing

materials depends upon the electrical resistivity. Materials having electrical resistivity greater than 2000 Ω.cm generally registered the tracks [Durrani and Bull, 1987]. The condition for stable latent track formation can also be expressed as a limiting value for material resistivity. However, there is no fixed value of resistivity above which the track formation always occurred. Hence, the material resistivity cannot serve as the unique property for track formation. Although the track formation technique is simple and well known, yet there is not a unique theory that explains the track formation. However, in the basic physical processes, the initial particle delivers their energy to the surrounding atoms of their path for a very short period of time and the stopping of the particle occurs within a time of the order of picoseconds. This process starts a series of ionizations and excitations that will create a lot of free electrons and damaged molecules in the vicinity of particle track. Due to the interactions of the damaged molecules new chemical species are created. During etching, the interactions of these new chemical species with the etching solution are stronger than that with the undamaged detector material. There are mainly two types of SSNTD's.

2.2.1 CR-39 Detectors

CR-39 (Columbia Resin-39) is the most versatile and most sensitive track detector with the trade name of the thermoset plastic which is a homopolymer of allyl-diglycol carbonate. It's simple formula is $(C_{12}H_{18}O_7)_n$. It is used to detect the α-particles having a wide energy range (several tens of MeV) while for protons of energy up to 10 MeV [Durrani and Bull, 1987]. CR-39 is highly isotropic, homogenous, and relatively stable to the environmental conditions. Several researchers studied the properties of CR-39 and confirm that it is a desirable solid state nuclear track detector [Al-Najjar and Durrani, 1984; Green et al., 1982]. The track recording efficiency of CR-39 depends on the processing conditions and therefore it can be modified, to some

extent, by the processing conditions adopted. This processing condition includes etchant type, strength, temperature, and etching time. A lot of work has been carried out to optimize the etching conditions using NaOH and KOH [Durrani and Bull, 1987].

2.2.2 LR-115 Detectors

LR-115 detectors consist a thin layer of deep red cellulose nitrate film coated on a 100 μm thick polyester base. Based on the thickness of cellulose nitrate layer, LR-115 detectors divided into two types. The type-I films have 6 μm thick cellulose nitrate coating, while type-II have 12 μm cellulose nitrate coating. The cellulose nitrate film is sensitive to alpha particles. The chemical composition of cellulose nitrate film is $C_6H_8O_6N_{12}$ and its specific gravity is 1.4. The film records the tracks of alpha particle having energy in the range of 1.9 - 4.2 MeV [Somogyi, 1986]. This energy range exists for these films due to its very special design and the less sensitive cellulose nitrate layer. Due to this energy range, LR-115 type II plastic detector does not record the background tracks from a thin layer of air that may exist between its active surface and the protecting paper. It starts recording only when its sensitive surface is open to the atmosphere or is in contact with an alpha source emitting alpha particles having energy within the energy range (1.9 - 4.2 MeV).

2.3 Advantage of SSNTD's

Some of the main advantages of SSNTD's [Shafi-ur-Rehman, 2005] are listed below.

a. They are relatively inexpensive in comparison to other detectors.

b. They are sensitive to radiation of high Linear Energy Transfer (LET) but are insensitive to beta, gamma and X-rays.

c. Simple chemicals (i.e. NaOH, KOH) are required to etch the detectors in order to

make the tracks visible in polymers, mineral, crystals and glasses. This process can be done in ordinary daylight i.e. no requirement of the darkroom.

d. They are integrating devices and produce a cumulative record over a period of time.

e. Permanent record of measured exposure (unlike the TL where red out destroys the record).

f. Track recorded in geological and extraterrestrial samples (meteriorites) remain intact for millions of years.

g. They are passive detectors and do not require power supplies during its use, in contrast to electronic detectors such as ionization chamber.

h. They are small, durable and thus can be used in homes for indoor radon measurements as well as in application where small geometry is important.

2.4 Disadvantage of SSNTD's

Besides their advantage, SSNTD's have the following disadvantages.

a. During the etching process only a part of the total etchable track length of the particle trajectory can be seen and the remaining part that has been etched off cannot be recovered.

b. Although charge and mass resolution of particles has been possible with them, an accurate resolution has still not been possible.

c. The monitoring of the experimental observations is not possible during the experiment.

2.5 Tracks Formation

In CR-39 the range of an alpha particle (energy 6 MeV) is about 40 μm, which means that on the average ~3700 ion pairs are created per micrometer (or 3–4 ion pairs per nanometre). Due to this primary ionizing process a series of new chemical processes started which creates the free chemical radicals and other chemical species.

These free chemical radicals and other chemical species make an enriched zone along the path of the alpha particle. This damaged zone is called a latent track. In conductive materials and in semiconductors, the process of recombination occurs and the latent tracks are not stable. A comprehensive survey of the materials that show the track effect is given by Fleischer et al. [Fleischer et al., 1975].

As a result of the electronic and atomic collision-cascades, a cloud of interstitial atoms and vacancies are formed in the close vicinity of the ion trajectory. In inorganic solids, energy of the order of 10–15 eV is required to remove an atom from its original position and displace it to the other side. On the other hand the organic plastic detectors being made of long chains of molecules, the energy required to break the chain is considerably low i.e. 2–3 eV. To explain the track formation mechanism, several models has been proposed. Some of them are, primary ionization criterion, Radius-Restricted Energy Loss (RREL), Total Energy Loss model (dE/dx), Linear Event-Density (LED), Secondary-Electron Energy Loss, and Restricted Energy Loss (REL) [Durrani and Bull, 1987]. The important features of the track core formation may briefly described by the following two models.

2.5.1 Thermal Spike Model

In this model it is assumed that the passage of an energetic particle produces intense heating of the localized region in the lattice. This energy loss leads to electronic and atomic collisions. The energy involves within atomic collision-cascade deposits in the close vicinity of the ion trajectory. The thermal spike model simplifies the complex effects of the atomic collision-cascade by assuming a simple thermal distribution. According to this model the deposited energy corresponds to an abrupt temperature rise in a small cylindrical volume around the ion trajectory at the time of passage $t = 0$. With the passage of time i.e. for $t > 0$, thermal energy diffuses away from

the ion trajectory. The thermal spike creates defects via thermal activation which are remaining as 'frozen defects' along the ion trajectory due to the rapid quenching of the temperature. In order to register the track on a material their heat conductivity should be low. In insulators the electron-phonon collisions are expected to be the predominant energy loss process and the excitation is communicated to the lattice more efficiently in such materials. This explains the inability of metals to show etchable tracks as the thermal spike becomes too broad and diffuses in the metal lattice, whereas in insulators a narrow intense spike is produced which leads to sufficient localized radiation damage capable of producing etchable tracks.

2.5.2 Ion-Explosion Spike Model

The mechanism of latent track formation based on the ion explosion spike model is shown in fig 2.1. According to this model when a charged particle passes through an insulating material then due to the coulomb interaction it produce a high concentration of positive ions along its path. If the recombination time is long compared with the lattice vibration time ($\sim 10^{-13}$ s) mutual repulsion drives the ions into interstitial positions and leave off a vacancy rich cylindrical core. For track formation, the electrostatic stress (i.e. the coulomb repulsive forces within the ionized region) should be greater than the mechanical strength or lattice-bonding forces. The maximum permissible density of free electrons must be low. This condition restricts the track formation to good insulators and excludes metals. The positive ion core contains a high concentration of holes. The tracks will not be formed in materials having high hole mobility. This model is currently the most widely accepted in the track field.

2.5.3 Track Formation in Inorganic Solids

In an inorganic solid, a systematic array of atoms has been found. When a heavy

charged particle passes through the solid it excites as well as ionizing the atoms of solids in its way. The primary damage in inorganic solids due to this excitation and ionization caused by the incident heavy ion is believed to be mainly responsible for the development of the etchable track i.e. for higher chemical etchability of the damaged trails. There is a strong evidence to accept that the secondary effects of delta rays are important in inorganic solids [Maurette, 1970; Seitz, 1972].

According to the ion-explosion model the formation of the track in inorganic solids shows systematically. In figure 2.1, the incoming heavy ion first knocks out the electrons (black circles) from the atom in its way, thus creating an unstable array of adjacent positive ions (figure 2.1a). These positive ions repeals and knock out one another away from their normal sites into the interstitial position in the crystal lattice, thus creating the vacant lattice sites due to their coulomb repulsive force (figure 2.1b). Thereafter the elastic relaxation reduces the internal local stress by spreading the stress more widely (figure 2.1c) [Somogyi and Szalay, 1973]. Due to the creation of a long range strain in the third step it is possible to observe the latent damage trails using the Transmission Electron Microscope (TEM). The damage produced by the atomic collision consists of displaced atom and resultant vacancies can be detected preferentially with respect to the host.

2.5.4 Track Formation in Polymers

In organic polymers, a number of broken polymers or scissions observed after the passage of a heavily charged particle as shown in figure 2.2. At the points of scission chemically reactive sites are formed, which may be enlarged when an etchant (i.e. NaOH) enters the damaged region by dissolving the distorted and degraded portions. By acquiring considerable vibrational energy both ions and excited molecules undergo bond rupture to form a complex array of stable molecules, free

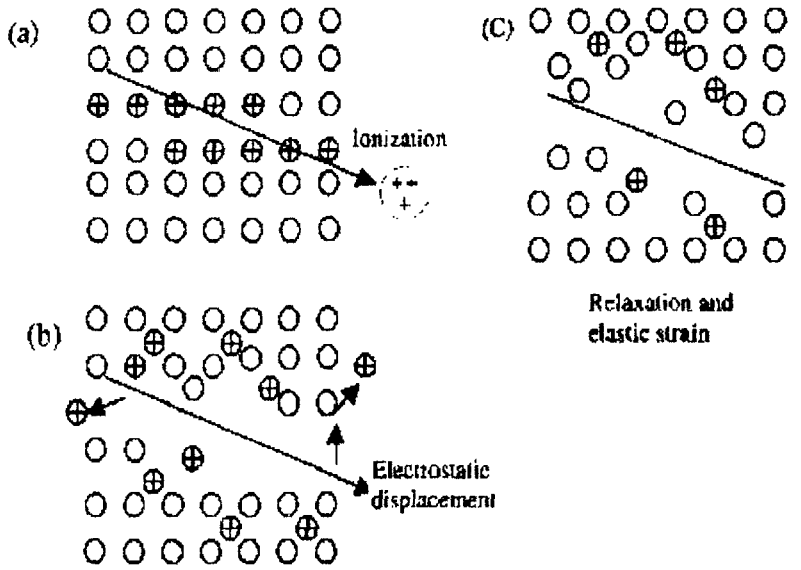

Figure 2.1 *Track formations in inorganic solids by Ion Explosion Spike mechanism [Fleischer et al., 1975]*

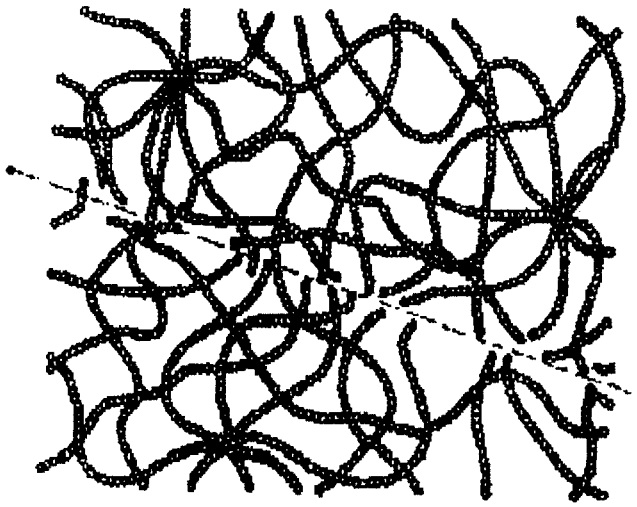

Figure 2.2 *Schematic diagram of track formation in polymers [Somogyi and Szalay, 1973]*

radicals and ionized molecules. The net effect on the plastic is the production of many broken molecular chains and production of a damaged region known as latent tracks. The latent track is chemically transformed or removed by an etchant that leads to an observable etched track. The evolution of track shape during the etching process depends mainly on the ratio of track etch rate V_T and bulk etch rate V_B.

2.6 Chemical Etching

The process of enlarging the size of the latent tracks produced by heavily ionizing particles is called etching and the solution used for this purpose is called etchant. Table 2.1 shows the etching conditions for different detectors. The size of the track depends upon the concentration of etching solution, etching time and temperature. In order to etch the detectors, an elastic spring (holding many detectors) is attached to a wire and immersed in to the etching solution within a beaker covered with a glass lid to avoid evaporation. After that the beaker is placed in a constant temperature water bath (figure 2.3). At the end of the etching, the detectors are removed and washed under running tap water in order to remove the etching residue from the etch pits. After drying, the detectors are counted for tracks under an optical microscope. Initially the track diameters are few micrometers in size but grows larger after prolong etching. During the chemical etching process, the solution (etchant) preferentially attacks the damaged core of the track and penetrates along its length with track etch velocity V_T while the surrounding undamaged material is attacked at a lower rate of bulk etch rate V_B, the bulk etch rate velocity. In general for a given etching conditions, V_B is constant, whereas V_T depends on the amount of damage present in the core region. Track development is governed by the ratio $V = V_T/V_B$ but when $V \leq 1$ track formation is not possible.

Table 2.1 Etching conditions for some detectors [Azam, 2002]

Detector	Etching conditions
Soda lime glasses	48% HF, 22^0C
Vitreous quartz glass	48% HF, 22^0C
Muscovite mica	48% HF, 22^0C
Makrofol-E	6N NaOH, 50 ± 1^0C
Makrofol-N	6N NaOH, 50 ± 1^0C
Lexan	6N NaOH, 50 ± 1^0C
Melixen-O	6N NaOH, 60 ± 1^0C
CR-39	6N NaOH, 70 ± 1^0C
Hostaphan	33% 6N NaOH+33% H_2O+33% CH_3OH, 40 ± 1^0C
LR-115 Type-II	2.5N NaOH, 60 ± 1^0C, 2 h

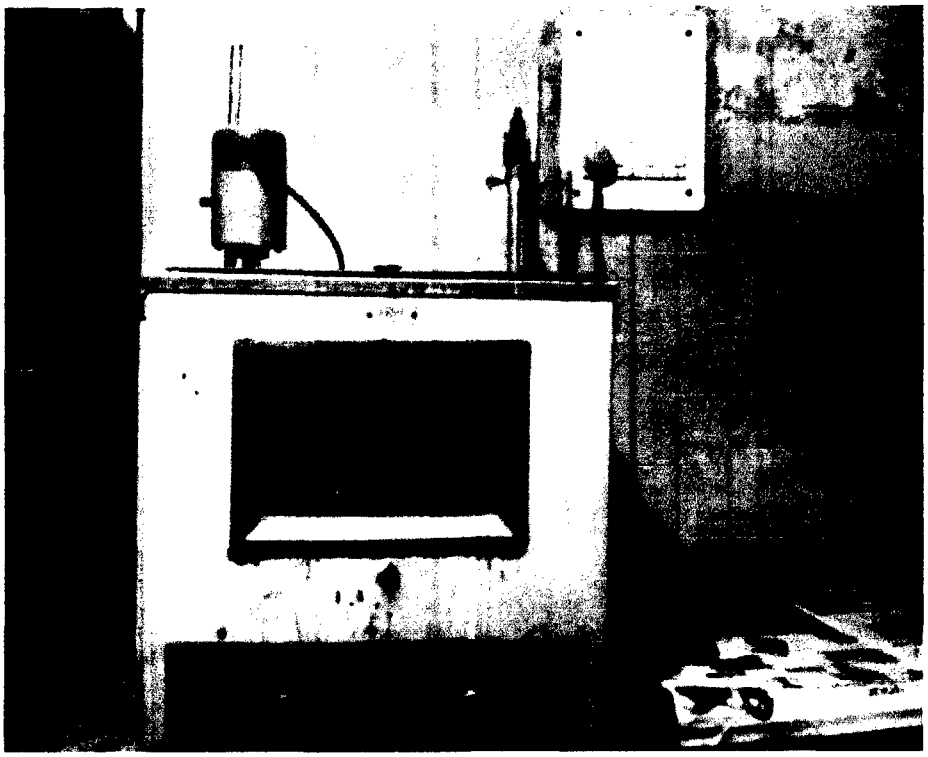

Figure 2.3 *Temperature controlled water bath*

In other words, we can say that the condition $V > 1$ must be fulfilled for track formation. The track formation takes place when the incident particle strikes a detector under normal incidence with respect to the detector surface. The tracks formed in this case are circular in shape [Shafi-ur-Rehman, 2005]. The parameters that are used to describe the geometry of etched tracks are shown in figure 2.4. Where, R = full length of the latent track (unetched), L = length of track attacked by the etchant up to a given moment, L_e = observed length of the etched track, h = thickness of the surface removed by etching and d = diameter of the etch-pit opening.

Now, the linear rate of attack down the track is V_T, is assumed to be very small compared to the final dimensions of the etched track, hence during etching time t, the etch pit will extend to a distance L from the origin, where $L = V_T\ t$. However, the surface is also being removed at a rate V_B, so the length of the etch pit is

$$L_e = V_T t - V_B t \qquad (1)$$

From Figure 2.4, the formation of a cone with semi-cone angle δ is given by

$$Sin\ \delta = \frac{V_B t}{L} = \frac{V_B t}{V_T t} = \frac{V_B}{V_T} \qquad (2)$$

The angle $\delta = \mathrm{Sin}^{-1}(V_B/V_T)$ is also known as the critical angle of etching (θ_c). The Materials in which V_T is not very much greater than V_B, such as glasses, etched tracks with large cone angles are produced while in the case where $V_T >> V_B$, such as plastic and minerals, tracks like long needles with smaller cone angles are produced.

From the triangle O'PT (fig. 2.5)

$$\frac{d\ /\ 2}{L_e} = \tan\ \delta \qquad (3)$$

From equation (2)

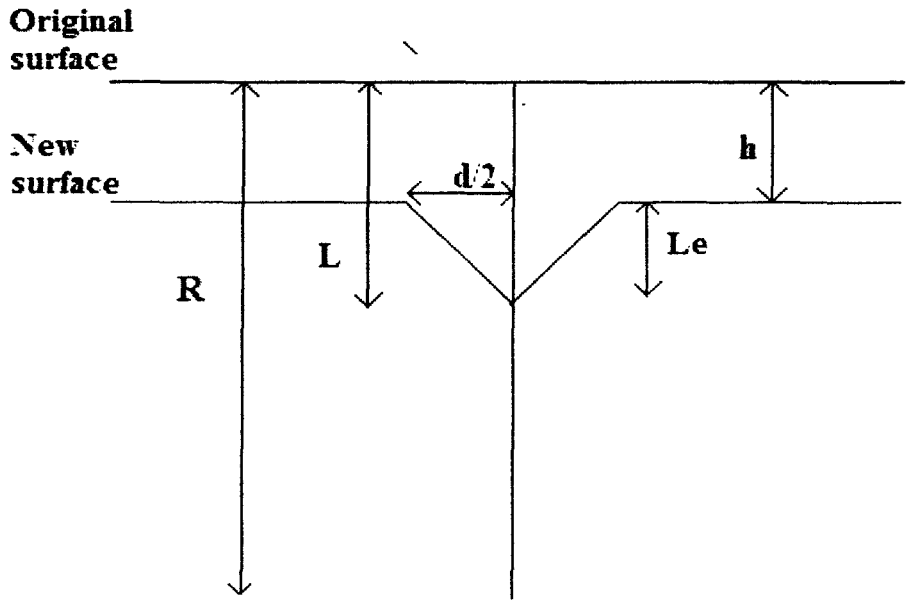

Figure 2.4 *Some parameters used to describe the geometry of the etched tracks*

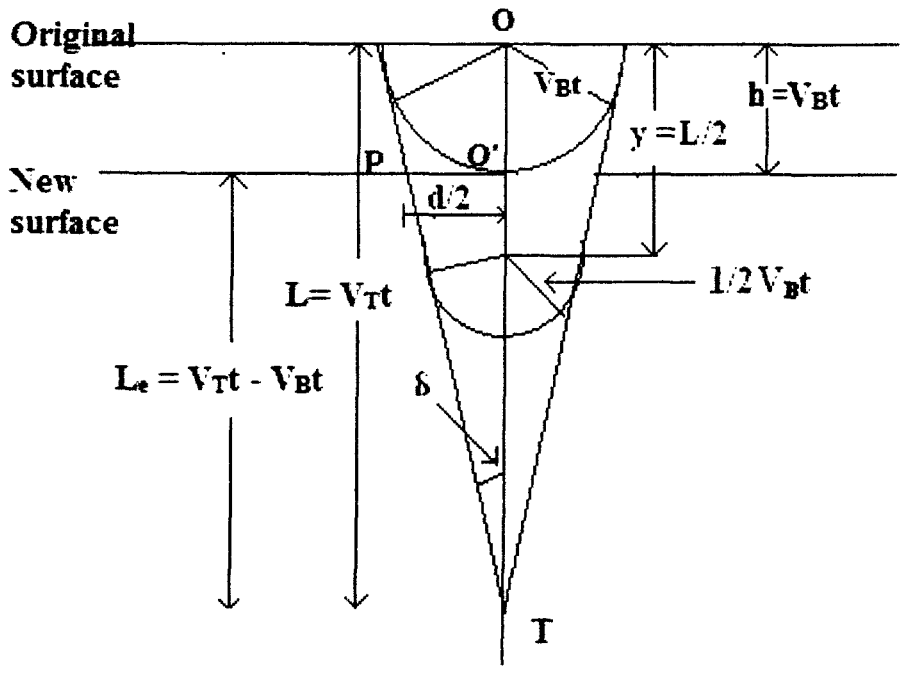

Figure 2.5 *Schematic diagram for the calculation of etched track parameter for a track of constant V_T, lying normal to the detector surface.*

$$\tan \delta = \frac{V_B}{\sqrt{V_T^2 - V_B^2}}$$

So from equation (3)

$$d = \frac{2V_B L_e}{\sqrt{V_T^2 - V_B^2}}$$

Using value of L_e from equation (1)

$$d = \frac{2V_B (V_T - V_B)}{\sqrt{V_T^2 - V_B^2}}$$

or

$$d = 2V_B t \sqrt{\frac{V_T - V_B}{V_T + V_B}} \qquad (4)$$

From the above relation we can calculate the diameter of the latent track [Durrani and Bull, 1987]. The diameter of the surface opening of etched tracks increase with increasing V_T, reaching a maximum of $2V_Bt$ when $V_T >> V_B$.

In most real applications, the incident particles strike the detector with oblique incidence instead of normal incidence. But in case of radon and its progenies, alphas or cosmic rays all incident angles are possible. It is, therefore, important to describe track growth for oblique incidence. This problem was considered in detail by Somogyi and Szalay [Somogyi and Szalay, 1973]. The cross-section between a track in the conical phase and the post-etching surface is an ellipse and the corresponding track opening is elliptical. The ellipse is characterized by its major axis D and its minor axis d. These two parameters are important characteristics of a track opening for oblique incidence. According to Somogyi and Szalay during the etching, the major axis of the track opening passes through three phases, while the minor axis develop through two phases. After some lengthy calculations, it can be shown that the major axis diameter of elliptical track is given by the following equation [Durrani and Bull, 1987]

$$D = \frac{2V_B t\sqrt{V_T^2 - V_B^2}}{V_T Sin\ \theta + 1} \qquad (5)$$

Whereas the expression for minor axis d of the track opening, could be calculated using the following relation

$$d = 2V_B t\sqrt{\frac{V\ Sin\ \theta - 1}{V\ Sin\ \theta + 1}} \qquad (6)$$

In order to determine V_T, CR-39 is usually irradiated with ^{252}Cf fission fragments at normal incidence. Then for $\theta = 90^0$, the relation for d can be written as

$$D = d = 2V_B t\sqrt{\frac{V - 1}{V + 1}} \qquad (7)$$

Where $V = V_T/V_B$. As the track etch rate for fission fragments is very much higher than the bulk etch rate (so that $V >> 1$) the above equation reduces to

$$D = d \cong 2V_B t$$

$$V_B \cong \frac{D}{2t} \qquad (8)$$

Thus a measurement of the diameter of the normally incident fission-fragment tracks at a known etching time yields a value for the bulk etch rate.

2.7 Track Counting

There are several methods used for the counting of tracks, some of them are briefly discussed here.

2.7.1 Optical Microscope

It is the most suitable method used for the counting of tracks in SSNTD's. After the chemical etching of a SSNTD's, the tracks of the particles can be easily counted by using an optical binocular research microscope (figure 2.6) at a magnification of 100X to 1500X. In the case of normal or near normal incidence, the microscope can be focused on the surface of the detectors where the intersection of the conical tracks with the

surface is observed as dark circular spots. The tracks can be easily distinguished from the background scratches etc. in the detectors. In some cases the total number of tracks and in some other track density (tracks/cm^2) are required. For finding track density, tracks are counted in about 50 to 100 fields and average is determined. A square graticule in the field of view is calibrated for its area by using a stage micrometer glass slide.

2.7.2 Spark Counting System

This technique was first invented by Cross and Tommasino in 1970. The schematic diagram of spark counter is shown in figure 2.7. This technique is efficient, fast, reliable and does not require highly expensive and sophisticated equipment [Monin, 1970]. Now days it is widely used in most of the laboratories around the world. It is especially useful for the counting of low track densities. In this system a thin detector of thickness 10-20 μm (in which the tracks are etched) is placed between a high voltage electrode and a thin aluminum (Al) electrode. The thin Al-electrode is an aluminized polyester electrode such as aluminized myler. When a high DC voltage through an RC network is applied a spark occurs through one hole in the film. The energy carried out by spark is sufficient to evaporate an area (< 0.1 mm in diameter) in thin electrode, leaving the corresponding hole electrically isolated which inhibits the occurrence of further spark in it. The spark therefore passes through another hole, jumping from one hole to another until it has passed through all the holes and the discharge then stops. As a result, the thin Al-electrode are removed exhibits the distribution pattern of the track on the original detector and allow their counting by naked eye, if not too numerous. The current pulses of the sparks can also be counted directly by the scalar. Besides these two methods there are some other methods have also been developed for track evaluation but they have still not found a great popularity among trackologists because of their inherent problems.

***Figure 2.6** Optical microscope*

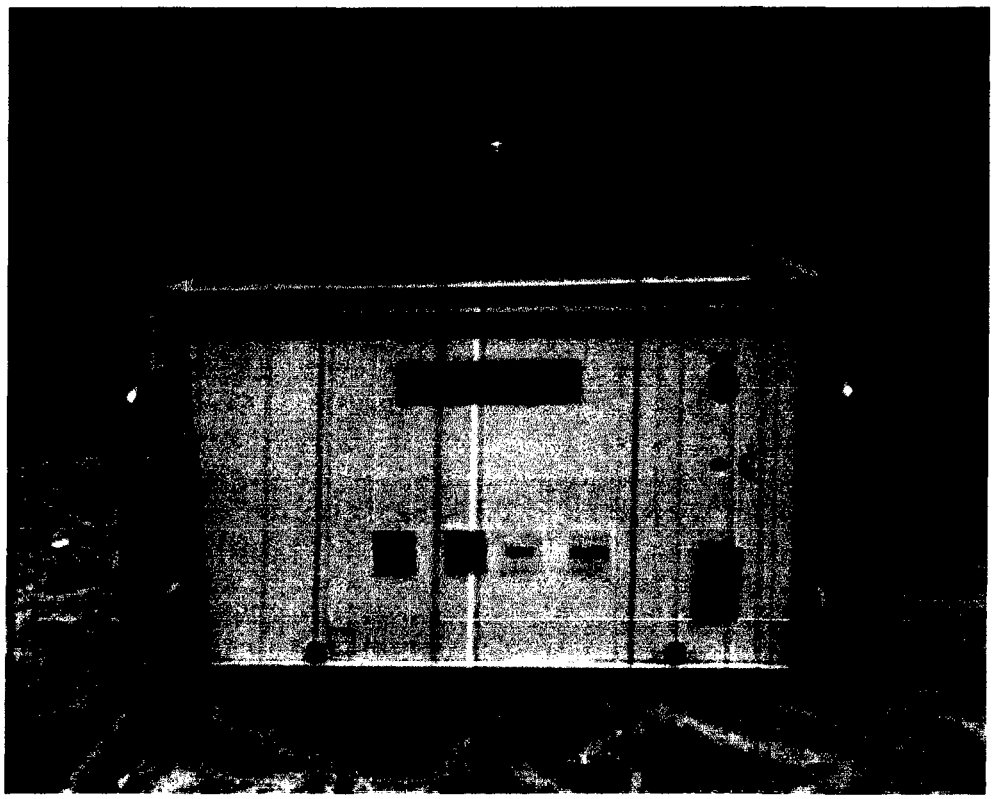

***Figure 2.7** Spark counting system*

These methods are

a. Scanning Electron Microscopy and Replicating Technique

b. Track counting by Reflectance and Transmittance measurements

c. Counting with unaided eye using the Projection Microscope or Slide Projector

d. Automatic Scanning using Electron circuit or Image Analyzing Devices with Optical Microscope

e. Automatic Scanning using Jumping Spark Technique

f. Locating Charged Particle Tracks by naked Eye

g. Track counting by Conductivity measurements through Etched Tracks

2.8 Twin Chamber Dosimeter Cups

Several methods have been reported in the literature for measuring the concentration of radon, thoron and their progeny to which a person working in the underground environment is expected. Most of these methods were developed during studies related to the health problems of mine workers [Denman and Parkinson, 1996; Qureshi et al., 2000; Furuta et al., 2002; Ward et al., 1977]. The concentrations of radon, thoron and their progenies are measured in the dwellings using Solid State Nuclear Track Detectors (SSNTDs), which are thin sheets of dielectric materials such as cellulose nitrate and polycarbonate. SSNTD's are more sensitive to alpha compared to beta and gamma radiations. For Indoor measurements LR-115 type II (Kodak Pathe, France) plastic track detectors were preferred. The films are less influenced by the moderate humidity, heat and light. The double chamber dosimeter cup used for monitoring radon, thoron and their progeny is shown in figure 2.9 a, b. It consists of two chambers; each chamber has a length of 4.5 cm and a radius of 3.1 cm. The LR-115 type II plastic track detectors were exposed in three different modes: (1) Bare mode, (2) Cup with filter paper and (3) Cup with membrane.

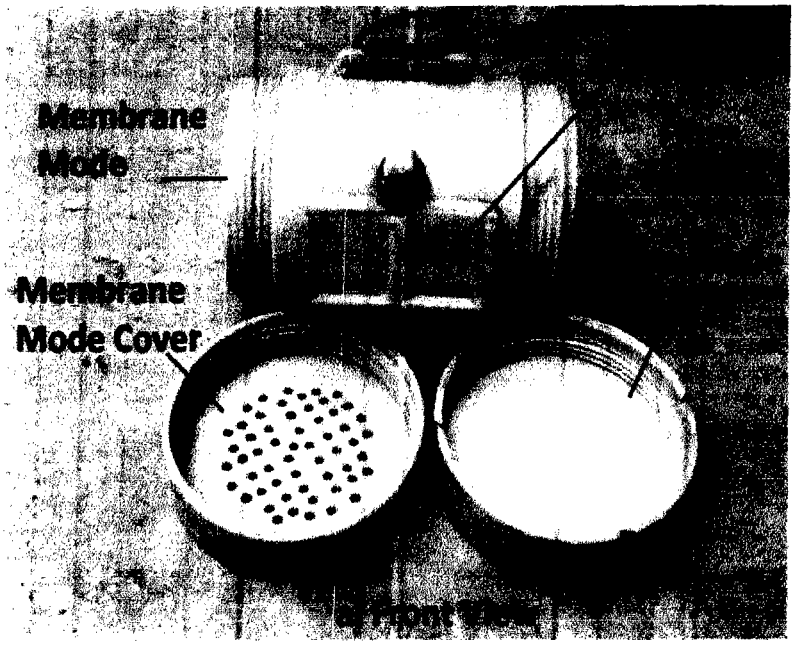

Figure 2.8 a Actual photograph of front view of twin cup dosimeter

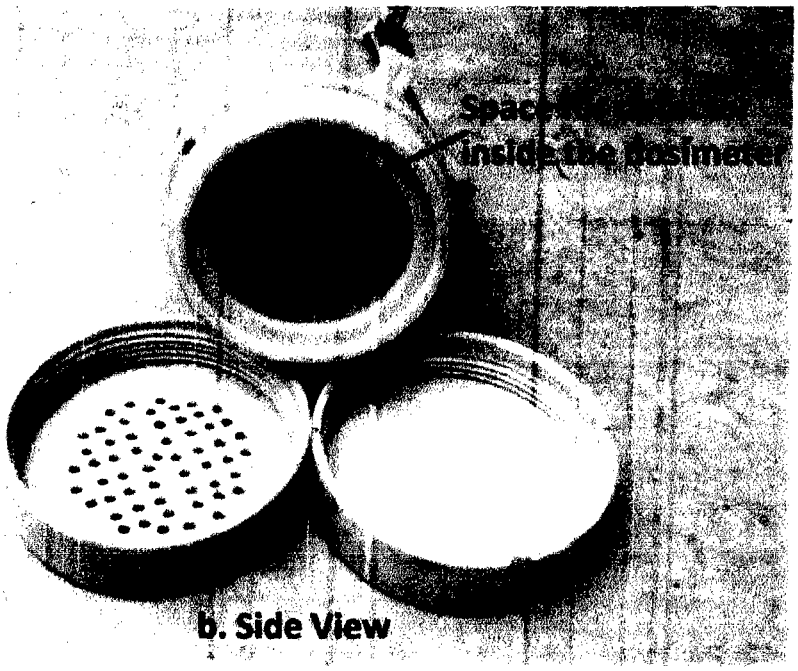

Figure 2.8 b Actual photograph of side view of twin cup dosimeter

These three modes give the radon and thoron gas in $Bq.m^{-3}$ and PAEC of individual progenies in terms of mWL units. The films used in the dosimeter are of approximately 12 μm thickness. The SSNTD-1 placed in membrane mode measures only radon which diffuses into the chamber from the ambient air through a semi-permeable membrane [Ward et al., 1977]. These membranes allow more than 95% of the radon gas to diffuse and reduce the thoron concentration to the extent of 1% or even less [Ramachandran et al., 1987; Jha et al., 1982; Wafaam, 2002]. On the opposite side, the glass fiber filter paper allows both radon and thoron gas to diffuse in and hence the tracks on SSNTD-2 are a measure of concentration of both gases. The SSNTD-3 exposed in the bare mode registers alpha tracks attributable to the airborne concentrations of both the gases and their progeny. The Twin-Chamber dosimeter cups fitted with detectors were installed inside the rooms in the houses. The detectors were installed in such a way that any wall or surfaces (like ceiling and roof) is not closer than 10 cm. The cups were exposed for 90–95 days after which they were retrievedThe choice of the house was random and one and only one room in each house was selected for the measurement. The latent tracks registered on the detector can be enlarged to microscopically visible size by chemical etching. The measurement of optically visible tracks is performed using an optical microscope under magnification of 100X. The recorded track density was used to calculate the concentration of radon, thoron and their progeny by using appropriate calibration factors and mathematical relations [Mayya et al.,1998; Doi et al., 1994; Shafi-ur-Rehman et al., 2006].

2.9 Bare Mode Technique

In the present study LR-115 type II plastic track detectors (SSNTDs) have been used for the measurement of radon and their progeny in indoor environments. Due to its being sensitive to only a specific range of energy, LR-115 type II detector is ideal for the

use as radon dosimeter even in bare mode as it's free from plate out effect [Abujarad et al., 1980]. In bare mode the detectors of size 2 cm x 2 cm were used as passive detectors [Alter and Fleischer, 1981], for recording the tracks of a-particles emitted by radon and its short-lived decay products present in the ambient air. These detectors were hanging in dwellings at a height of about 10 feet from the floor for exposure of about three months. During the exposure period, the alpha particles (energy between 1.7–4.1 MeV) originating from radon and its short-lived decay products were registered as tracks on the detectors [Jonsson, 1981; Durrani et al., 1984]. Thus, the radon short lived decay products, which plate out on the surface of the detectors will not be detected because their α-particles are too energetic [Cherouati, 1988]. After exposure, the detectors were retrieved and etched for 2 h in 2.5 N NaOH solution at 60 ± 1^0C in the laboratory. Subsequently, the tracks were counted using an optical microscope at a magnification of 100X. The track density registered in bare detectors will, therefore be a function of radon progeny concentration in air.

2.10 Can Technique

The gaseous radioactive isotope of radon has a significant share in the total quantum of natural sources of exposure. The most important source of background radioactivity is soil because it contains naturally occurring radioactive materials. Exhalation of ^{222}Rn, alpha-radioactive inert gas, is associated with the presence of ^{226}Ra and its ultimate precursor uranium in the earth's crust. Their exhalation from the earth's crust and from the building materials, form the main sources of these gases in the outdoor and indoor environments. Although these elements occur in virtually all types of rocks and soils, their concentration varies with specific sites and geological materials [Somogyi et al., 1986].

The 'can technique' [Abujarad et al., 1980; Khan et al., 1992] is used for the measurement of radium and radon exhalation rate in some soil samples collected from different places of different cities. The dried samples are finely powdered and sieved through a 200 mesh sieve. About 100 g of fine powdered samples is placed in a Can of 10 cm in height and 7 cm in diameter and sealed for 30 days to attain the equilibrium. After one month, LR-115 type II detectors are fixed on the lower side of lids, The Cans are then sealed and left as such for 90 days so that the detectors can record the tracks of α-particles resulting from the decay of radon. After the exposure period, detectors are etched in 2.5 N NaOH solution at 60 °C for 90 minutes using a constant temperature water bath. These etched tracks are counted by using an optical microscope at 100X magnification. The obtained track density is used to calculate the radon exhalation rate and radium concentration by using the appropriate relations.

2.9 Study Area

The area studied by us i.e. Bareilly Faizabad and Farrukhabad (figure 2.4) of Uttar Pradesh lie in the Indo-Gangetic or Ganga plain and falls under the sub-tropical climate zone [Umar and Ahmad, 2000]. The State of Uttar Pradesh has an area of about 240,928 km^2. It extends from $23^0 52'15"$ to $30^0 25'50"$N latitude and $77^0 50'36"$ to $84^0 38'10"$E longitude and is characterized by rock formations ranging in age from the Archean (the Bundelkhand Granitic gneisses) to the recent (the Ganga alluvium). The Gangetic Plain, which dominates the landscape and nearly covers three-fourths of the geographical area of the state lies, between the rocky Himalayan belt in the northern and southern hilly tract comprising mainly Pre-Cambrian rocks. Flexing of the Indian lithosphere in response to the compressive forces due to collision and thrust fold loading produced the Gangetic Plain Foreland basin. It is filled with recent alluvial sediments, which are at places more than 1,000 m thick and contain an amalgam of sand, silt and clay in varying proportions

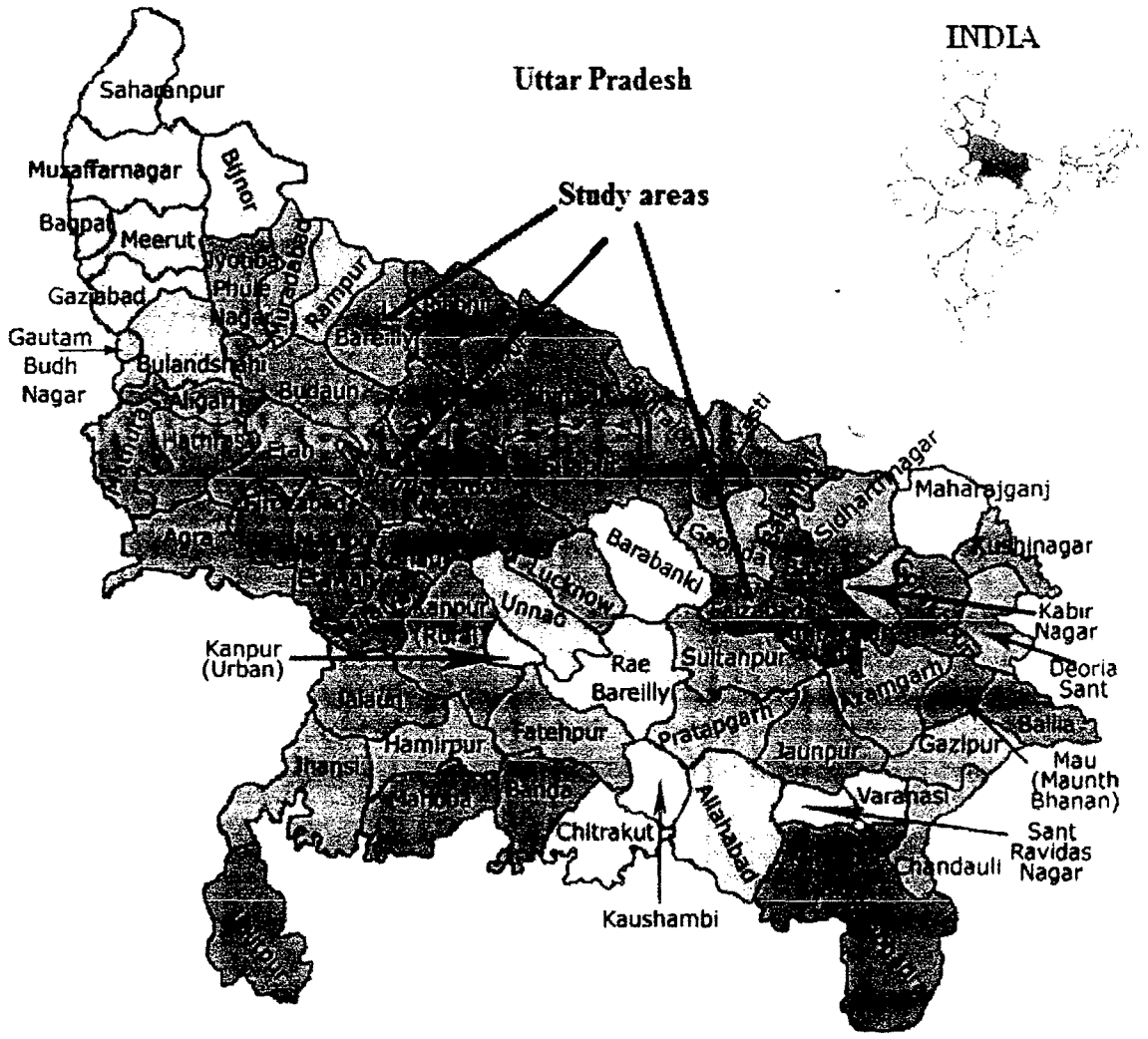

Fig. 2.9 The areas studied for radium, radon and thoron measurements

[Umar and Ahmad, 2000]. The southern hilly tract is roughly parallel to the Ganga-Yamuna lineament. The tract is underlain by granitic complex in the Bundelkhand region and Sonbhadra. It is overlain by rocks of Mahakoshal (Bijawar) and Vindhyan Supergroup. The younger rocks comprise coal-bearing Gondwana rocks in the southwestern area of Sonbhadra and basaltic rocks in the southern part of Lalitpur. The granitic complex is considered to be a potential for the search of metallic minerals such as copper, lead, zinc, molybdenum, gold and nickel, Uranium and Platinum group of elements. The overlying sediments of Mahakoshal (Bijawar) and associated iron formation show a potential for the search of copper, uranium and gold in Lalitpur, and andalusite, sillimanite, gold, calcite, marble and clay in Sonbhadra. The lower Vindhyan sediments of Sonbhadra contain deposits of cement-grade limestone, flux-grade dolomites and building stone, and are also a potential for the search of placer gold and other metals, while the Upper Vindhyan sandstones are suitable for making decorative slab/tiles. Deposits of silica sands and bauxite are available in Allahabad and Chitrakoot districts.

The alluvium soil is the most important soil in this state and occupying nearly 61.8 per cent of the total area of Uttar Pradesh. They were excessively deep soils and have developed from the alluvium deposited by the two major rivers of the state the Ganga and the Yamuna and their tributaries, The alluvial material deposited by the Ganga and its tributaries is derived from the soft dolomite rocks of the Himalayas and that deposited by the Yamuna and its tributaries owes its origin to the basaltic rock of central Indian hills [Singh, 1971].

3.6 Selection of the Dwellings

To select the dwellings for our measurement, we approach the residents personally. Most of the residents thought that these detectors were spying equipments like

camera that may breach their privacy. Thus, they did not allow hanging our detectors into their dwellings. Then we try to convince the parents through their school going children and some of them respond positively. They gave their consent to install the detector. However there were several other constrains due to which it was not possible for us to install the detectors in all these dwellings. Therefore we decided to shortlist the number of dwellings. We have chosen those dwellings that were relatively the best representation of the built-up area. Then the dwellings divided into categories according to their construction and ventilation conditions. Detectors were mounted vertically at the locations where the dust collection on the detectors is minimised.

3.7 Construction of Dwellings in the Study Area

There was a marked differences observed in the construction of dwellings in the study area. Baked bricks and dressed stones were the main construction materials used in the construction of the outer walls of the dwellings. Some of them were plastered with the mixture of cement, sand and mortar and painted/whitewash, while some were unplastered. In some dwellings the walls were covered by the tiles or stones. Reinforced cement concrete or bricks (RCC/RCB) were used for the construction of roof of more than half of the dwellings. Backed bricks, cement/iron sheets and wood/bamboo were the other construction materials used for the construction of the roof. In the study area a wide variation was observed in the floor construction. There were several types of floor like RCC floor, earthen floor, plain cemented floor covered with tiles/ marble chips/granite marble. Each dwelling has at least two rooms with one or more windows. These included both single and double story dwellings. In most of the cases, we install the dosimeters in the bedroom or drawing room of the selected houses situated at ground and first floor.

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CHAPTER-III

INDOOR RADON MAESUREMENTS IN FARRUKHABAD, FAIZABAD AND BAREILLY CITIES

3.1 Introduction

Measurement of indoor radon (^{222}Rn) is of importance because the radiation dose to human population due to inhalation of radon and its daughters contribute more than 50% of the total dose from natural sources [UNSCEAR, 2000]. Radon and its decay products contribute significantly to an increased risk of lung cancer to the population [Field et al., 2001]. Radon can originate from deeply buried deposits beneath the homes and can migrate to the soil surface. There are two major transport mechanisms that determine the amount of radon gas that enters into a residential building; (1) Advection, caused by the pressure difference across the foundation structure between the soil gas and the building (indoor) air and (2) Diffusion caused by the radon concentration gradient across the foundation structure between the soil and indoor air. Both these transport mechanisms are connected to the properties of intermediate media which separate the two regions. In indoors, the radon is mainly entered through the diffusion process [Renken and Rosenberg, 1995]. Radon diffusion and transport through different media is a complex process and is affected by several factors [Tanner, 1980; Singh et al., 1999].

Being relatively long lived, the gaseous radon has very little probability of breaking down while in the lungs, and thereby, may be exhaled in the process of respiration before undergoing a radioactive decay. The daughters of radon such as ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po are relatively short lived radioactive heavy metals. These daughters when drawn into the respiratory tract usually remain stuck in the 'mucus' lining of the tract and may be lodged in the lungs [James, 1987]. Upon decaying they deposit large amount of energy in the surrounding tissues results in a severe type of biological damage,

which may ultimately cause lung cancer [Jamil et al., 1997]. For these reasons, the dose deriving from the exposure to ^{222}Rn and their progeny in closed spaces has been placed in direct relation to the risk of lung cancer [ICRP, 1987; ICRP 1993]. It is well known that exposure to high concentrations of radon and its daughters for a long period leads to pathological effects like changes in the respiratory function and the occurrence of lung cancer [BEIR, 1999]. The epidemiological evidence for the induction of lung cancer through inhalation of radon comes from several case studies of underground miners. During recent years, several reports have appeared in the literature demonstrating the ever increasing interest in monitoring the radon in dwellings all over the world [Abu-Jarad and Fremlin, 1981; Keller and Folkerts, 1984; Nazaroff and Doyle, 1985; Ramachandran et al., 1986; Subba Ramu et al., 1990; Jonsson, 1991; Marx and Toth, 1997; Virk et al., 1999]. The results of the studies show that some countries (e.g. Sweden, Norway, Hungary and some parts of the USA) have high radon concentrations in many of their dwellings [Swedjemark and Mjones, 1984; UNSCEAR, 1988 20] and even in certain cases, doses from radon and its daughters to some people living in these areas may exceed those received by occupational workers. The main sources of indoor radon levels are the soil-gas, building materials, tap water and natural gas used for cooking. The topography, house construction type, soil characteristics, ventilation rate, wind direction, atmospheric pressure and even the lifestyle of the people, also significantly influence it [Stranden et al., 1979; Abu-Jarad and Fremlin, 1983]. It emphasizes the importance of long-term integrated measurements and hence indicating the importance of the SSNTD techniques in these measurements. In the present investigations, the passive technique using the cellulose nitrate (LR-115 type-II) plastic track detectors (SSNTDs) has been utilized for the comparative study of the indoor radon, thoron and their progeny levels in the dwellings of different cities of India.

3.2 Experiment Details

3.2.1 Measurement of Indoor Radon and Its Progeny (By Bare Technique)

In bare mode technique, the SSNTD films (LR-115 type II strippable film) of size 2 x 2 cm^2 have fixed on a card board containing the details of the occupant, exposure period, identification code, type of house, floor etc. We also used the dosimeter cups for bare mode exposure. The bare mode of exposure is considered to suffer from interference due to collection of dust particles on the detector surface. It has been reported that on an average of about 0.3 mg/cm^2 of dust load could affect the radon progeny estimation [Orzechowski et al., 1982]. Subba Ramu et al. [Subba Ramu et al., 1991] have reported that the dust collected over a three month exposure period in bare mode has been typically found to be less than 0.05 mg/cm^2. Since our exposure time for most of the measurements is equal to or more than 90 days, so the effect of dust load was ignored. Further, the bare mode exposure in the plane vertical to the ground minimizes the dust deposition. These detectors were suspended in each dwelling either in bedrooms or living rooms where the occupants generally spend a good percentage of their time, at a height of about 2.5 m from the ground level with their sensitive surface facing the air. Care should be taken that there is nothing to obstruct the detectors within a hemispherical volume of 9.1 cm in front of them. No surface should closer than this as the decay product would act as intermediate α-particles sources. The detectors were retrieved after an exposure period of three months and etched using 2.5 N NaOH solutions at 60°C for 90 min in a constant temperature bath, and washed for about 5 min in running water. The numbers of alpha tracks on the detector surface were counted by using an optical binocular research microscope at a magnification of 100X. Background track density was also measured for each detector. The value of radon progeny (PAEC) in mWL for radon progeny was estimated by using the following equation

$$C_P\ (mWL) = \rho / K \times t \qquad (1)$$

Where ρ is corrected track density in tracks/cm^2, t is the exposure time and K is the calibration or sensitivity factor which was determined by simulating the environmental conditions in Environmental Assessment Division of Bhabha Atomic Research Centre (BARC) Mumbai, India. The details of the experiment are reported elsewhere [Srivastva et al., 1995].

For the measurement of radon concentration (in Bq/m^3) following expression has been used [Kumar et al., 2003]

$$C_R(Bq/m^3) = WL_{cocn} \times 3700 / F_R$$

$$C_R(Bq/m^3) = PAEC(mWL) \times 3.7 / F_R \qquad (2)$$

Where F_R is the equilibrium factor for radon having the value 0.4 given by UNSCEAR [UNSCEAR, 2000]. A conversion factor of 3.88 mSv/WLM and an occupancy factor of 0.8 have been used in order to calculate the effective dose equivalent to human lungs [ICRP, 1993].

3.2.2 Measurement of Indoor Radon, Thoron and Their Progeny (By Dosimeter cups)

Indoor radon and thoron concentrations were measured using LR-115 type II plastic track detector using the twin chamber dosimeter cups. These dosimeter cups are obtained from the Environmental Assessment Division, BARC, Mumbai, India. The plastic detector films of size 2 x 2 cm^2 have exposed in these cups; each cup has two chambers, each with a height of 4.5 cm and diameter of 6.2 cm. The detectors are fixed at the bottom of each chamber, the mouth of one chamber being covered with glass fiber filter paper (filter mode) and the other with a semi-permeable membrane (membrane mode). These membranes have permeability constants in the range of 10^{-8} – 10^{-7} cm^2/s

[Jonsson, 1981]. The dosimeter cups also have provision for exposing the detector in bare mode on the outer side of the cup. The detector placed in membrane mode records alpha tracks due to radon (^{222}Rn) as the membrane allowing only radon to pass through it and suppressing the thoron to less than 1%. The mean time for radon to reach the steady state concentration inside the cup is about 4.5 h. The other detector placed in filter mode, records tracks due to alpha particles from radon and thoron. The bare detector records the tracks due to alpha particles from radon, thoron and their progeny and is used to determine radon and thoron progeny concentration in mWL (milli Working Level).

These dosimeters are suspended at a height of 2.5 m from the floor inside the houses. Care is taken to keep the bare detector at least 9.1 cm away from any wall surface. Due to this the errors due to tracks from depositing activity from nearby surfaces are avoided, since the ranges of alpha particles emitted by radon and thoron progeny do not exceed 10 cm in the air. At this position, the dosimeter records the average radon concentration inside the house. These dosimeters were left undisturbed in their places for about 90 days. After the exposure period the detectors have retrieved and chemically etched in 2.5 N NaOH solution at 60^0C for about 90 min in a constant temperature water bath to reveal the α-particle tracks. Some detectors have getting destroyed during etching. Subsequently, these α-tracks are counted using an optical microscope at a magnification of 100X. The concentrations of radon, thoron and their progeny are calculated using the following modified equations [Mayya et al., 1998; Sannappa et al., 2003]

$$C_R\,(Bq/m^3) = \rho_m / K_m.d \qquad (1)$$

$$C_T\,(Bq/m^3) = \left(\rho_f - d.C_R \times K_{rf}\right)/ K_{tf}.d \qquad (2)$$

Where C_R and C_T are the concentration of radon and thoron (in Bq/m^3) respectively, ρ_m is the track density of film in membrane mode (in tracks/cm^2), K_m is the

calibration factor of radon in membrane mode (in tracks.m^3 /Bq.cm^2.d), d is the time of exposure (in days), ρ_f is the track density of film in filter mode (in tracks/cm^2), K_{rf} is the calibration factor of radon in filter mode (in tracks.m^3 /Bq.cm^2.d) and K_{tf} is the calibration factor for thoron in filter mode (in tracks.m^3 /Bq.cm^2.d). The numeric values of these factors are given below

$K_m = 0.019 \pm 0.003$ tracks.m^3 /Bq.cm^2.d

$K_{rf} = 0.020 \pm 0.004$ tracks.m^3 /Bq.cm^2.d

$K_{tf} = 0.016 \pm 0.005$ tracks.m^3 /Bq.cm^2.d

The inhalation dose (in mSv/y) is calculated by using the following expression [UNSCEAR, 2000]

$$D\,(msv/y) = \{(0.17+9F_R)C_R + (0.11+32F_T)C_T\} \times 0.007 \quad (3)$$

Where, F_R and F_T are equilibrium factors for radon and thoron and having the value of 0.4 and 0.1, respectively [UNSCEAR, 1999].

The radon and thoron progeny levels or PAEC values (in mWL) calculated by using the equations [ICRP, 1993; Khan and Azam, 2012]

$$PAEC\,(mWL) = (C_R \times F_R)/3.7 \quad (4)$$

$$PAEC\,(mWL) = (C_T \times F_T)/3.7 \quad (5)$$

Annual exposure from radon and thoron progeny has been calculated by using the Generic relation [ICRP, 1981]. The values of life time fatality risk [Nikolaev and Ilic, 1999] are obtained by using a factor of 3 x 10^{-4} WLM^{-1}. A conversion factor of 3.9 mSv/WLM and 3.4 mSv/WLM for radon [ICRP, 1993] and thoron [UNSCEAR, 1993] progeny, respectively was used to calculate the annual effective dose.

3.3 Results and Discussion

3.3.1. Radon and Its Progeny in Dwellings of Farrukhabad City

Table 3.1 presents the experimentally measured values of PAEC in MWL, the concentration of radon in Bq/m^3 and effective dose in mSv/y in different dwellings of the Farrukhabad city of Uttar Pradesh, India. The values of PAEC found to vary from 5.04 to 9.91 mWL with an average value of 7.19 mWL. The values of radon concentration vary from 46.62 to 91.67 Bq/m^3 with an average value of 66.54 Bq/m^3. However, the value of effective dose found to vary from 0.80 to 1.58 mSv/y with an average value of 1.15 mSv/y. The values of PAEC and radon concentration may vary with the type of construction, ventilation condition and other factors of dwellings. In the study area there are mainly two types of houses, one (first types) which are constructed of brick walls with plaster and having cemented floor and concrete roof, while the others (second types) are made of brick walls without plaster and having earthen floor. The lower values of different parameters shown in the table 3.1 (i.e. from S. No. 1-8) found in the first type of houses. As these houses have plastered, painted and having cemented floor so there is a rare chance of radon emanation from the construction materials and ground soil which results lower radon levels. The higher values shown in the table 3.1 (i.e. from S. No. 9-19) corresponding to the second type of houses. In these types of houses, due to without plastered wall and earthen floor, the radon gas emanating from construction material and ground soil easily mix with indoor air and increase the radon level. According to ICRP the action level for radon concentration should be in the range of 200-600 Bq/m^3. It is seen from the table 3.1 that all the values of radon concentration are found below the level of concern i.e., 150 Bq/m^3 [Mc Laughlin, 1989]. The values of effective dose are also found lower than the worldwide average background radiation dose [UNSCEAR, 2000] of 2.4 mSv/y.

Table 3.1 *Values of PAEC, Radon concentration and Effective dose in different dwellings of study area*

S.No.	Corrected track density (ρ_b) tracks/cm^2	PAEC ($WL_{conc.}$) C_p (mWL)	Radon conc. (Bq/cm^3)	Effective dose (mSv/y)
1	290	5.04	46.62	0.80
2	290	5.04	46.62	0.80
3	300	5.21	48.19	0.83
4	320	5.56	51.43	0.89
5	330	5.74	53.09	0.92
6	340	5.91	54.67	0.94
7	360	6.26	57.91	1.00
8	370	6.43	59.48	1.03
9	390	6.78	62.71	1.08
10	400	6.96	64.38	1.11
11	430	7.48	69.19	1.19
12	450	7.82	72.33	1.25
13	450	7.83	72.43	1.25
14	470	8.17	75.57	1.31
15	490	8.52	78.81	1.36
16	510	8.87	82.04	1.42
17	540	9.39	86.86	1.50
18	560	9.73	90.20	1.55
19	570	9.91	91.67	1.58
Average		7.19	66.54	1.15
Standard Deviation		1.60	14.86	0.26

3.3.2 Indoor Radon, Thoron and Their Progeny in Farrukhabad City

Table 3.2 shows the concentration of radon, thoron and inhalation dose present in the dwellings at different places of the Farrukhabad city of Utter Pradesh, India. The concentration of radon and thoron varies from 45 to 79 Bq/m^3 and 10 to 50 Bq/m^3 with an average value of 59 Bq/m^3 and 28 Bq/m^3, respectively. The inhalation dose due to radon, thoron and their progeny were found to vary from 1.6 to 2.9 mSv/y with an average value of 2.2 mSv/y. Table 3.3 shows the radon, thoron daughters (PAEC) concentration, annual exposure due to radon and thoron, life time fatality risk and annual effective dose. The values of radon daughter's concentration (PAEC) vary from 4.9 to 8.6 mWL with an average value of 6.4 mWL while thoron daughter's concentration (PAEC) varies from 0.28 to 1.33 mWL with an average value of 0.75 mWL, respectively. The annual exposure from radon and thoron daughters collectively was varied from 0.23 to 0.39 WLM and the values of life time fatality risk was found to vary from 0.68 x 10^{-4} to 1.18 x 10^{-4}. However the values of the annual effective dose found to vary from 0.87 to 1.51 mSv/y with an average value of 1.13 mSv/y respectively. The variation in the values of radon, thoron and their progenies may be due to the difference in the type of construction of the dwellings. The lower values of different parameters shown in table 3.2 and 3.3 (i.e. from S. No. 1-5) corresponding to the dwellings having well concrete flooring, cement plastered, painted wall, large volume and good ventilation conditions. However, the dwellings have earthen flooring, without plastered and painted walls, small volume and poor ventilation condition corresponding to the higher values (i.e. from S. No. 6-10). In these types of dwellings, the radon present in the soil directly comes into the contact with the indoor air resulting increase radiation level. The values of thoron concentration in the present study correspond with the range of 5.7 to 42.2 Bq/m^3 reported for Indian dwellings by Ramachandran et al. [Ramachandran et al., 2010] but the average value of

Table 3.2 *Values of radon, thoron concentration and inhalation dose*

S.No.	Corrected track density (ρ_m) (Tracks/cm^2)	Corrected track density (ρ_f) (Tracks/cm^2)	Radon conc. (C_R) (Bq/m^3)	Thoron conc. (C_T) (Bq/m^3)	Inhalation dose (D) (mSv/y)
1	80	120	45	24	1.7
2	80	130	45	31	1.9
3	90	110	51	10	1.6
4	90	150	51	37	2.2
5	100	140	57	23	2.0
6	110	160	62	24	2.2
7	110	150	62	23	2.2
8	120	200	68	50	2.9
9	130	170	74	22	2.4
10	140	240	79	35	2.9
Average			59	28	2.2
Standard Deviation			12	11	0.4

Table 3.3 *Values of radon, thoron daughters (PAEC) concentration, annual exposure due to radon and thoron, life time fatality risk and annual effective dose*

S.No.	Radon daughters conc. (C_R) (mWL)	Thoron daughters conc. (C_T) (mWL)	Annual exposure (Rn) (WLM)	Annual exposure (Tn) (WLM)	Total Annual Exposure (Rn+Tn) (WLM)	Life time fatality risk factor ($x10^{-4}$)	Annual effective dose (mSv/y)
1	4.9	0.65	0.20	0.03	0.23	0.68	0.87
2	4.9	0.83	0..21	0.03	0.23	0.70	0.90
3	5.5	0.28	0.23	0.01	0.24	0.71	0.92
4	5.5	1.00	0.23	0.04	0.27	0.80	1.02
5	6.1	0.63	0.25	0.03	0.28	0.83	1.07
6	6.7	0.64	0.28	0.03	0.30	0.91	1.17
7	6.7	0.62	0.28	0.02	0.30	0.91	1.16
8	7.3	1.33	0.30	0.05	0.36	1.07	1.36
9	7.9	0.60	0.33	0.02	0.35	1.06	1.36
10	8.6	0.95	0.35	0.04	0.39	1.18	1.51
Av.	6.4	0.75			0.29	0.88	1.13
S.D.	1.3	0.29			0.06	0.17	0.22

thoron in our study found higher than the world average of 3 Bq/m^3 [Martinez et al., 2004]. The values of effective dose are found lower than the worldwide average background radiation dose of 2.4 mSv/y [UNSCEAR, 2000]. On comparing with the similar measurements performed by K Kant et al. (in winter season) [Kant et al., 2009] we found that our experimental values are slightly greater than their values. This may be due to the soil beneath the structure, use of construction materials having a more exhalation rate and the ventilation conditions of the dwellings. Almost all the values shown in table 3.2 and 3.3 are within permissible limit recommended by ICRP [ICRP, 1993].

3.3.3 Indoor Radon, Thoron and Their Progeny in Faizabad City

The concentration of radon, thoron and inhalation dose (in winter season) inside the dwellings of Faizabad city is summarized in table 3.4. The radon and thoron concentrations vary from 11.57 to 104.10 Bq/m^3 and 5.78 to 43.74 Bq/m^3, respectively. Their average values are 60.57 Bq/m^3 and 26.12 Bq/m^3, respectively. The inhalation dose due to radon, thoron and their progeny have been found to vary from 0.45 to 3.55 mSv/y with an average value of 2.21 mSv/y. Table 3.5 presents the radon, thoron daughters concentration, total annual exposure, life time fatality risk and annual effective dose. The values of radon daughters concentration (PAEC) vary from 1.25 to 11.25 MWL with an average value of 6.54 MWL, while thoron daughter's concentration (PAEC) varies from 0.16 to 1.18 mWL with an average value of 0.70 mWL, respectively. The annual exposure from radon and thoron daughters collectively varies from 0.057 to 0.502 WLM with an average value of 0.298, while the values of life time fatality risk has been found to vary from 0.17×10^{-4} to 1.51×10^{-4} with an average value of 0.89×10^{-4}. However, the values of annual effective dose from radon and thoron daughters vary from 0.22 to 1.93 mSv/y with an average value of 1.15 mSv/y, respectively.

Table 3.4 *Values of radon, thoron concentration and inhalation dose (winter season)*

S.No.	Position of dwellings	Radon conc. (C_R) (Bq/m^3)	Thoron conc. (C_T) (Bq/m^3)	Inhalation dose (D) (mSv/y)
1	FF	11.57	6.14	0.45
2	FF	17.35	5.78	0.59
3	FF	23.13	12.30	0.89
4	FF	28.91	11.94	1.08
5	FF	34.70	18.44	1.34
6	FF	40.48	31.81	1.80
7	GF	52.05	24.22	1.93
8	GF	57.83	30.72	2.23
9	GF	57.83	37.60	2.59
10	GF	63.62	30.36	2.38
11	GF	69.40	43.74	2.84
12	GF	69.40	36.87	2.69
13	GF	75.19	41.56	2.94
14	GF	80.97	36.15	2.97
15	GF	86.76	22.04	2.80
16	GF	86.75	28.92	2.95
17	GF	92.53	21.70	2.94
18	GF	98.32	21.33	3.08
19	GF	104.10	34.71	3.55
Average		60.57	26.12	2.21
Standard Deviation		28.23	11.49	0.93

Table 3.5 *Values of radon, thoron daughters (PAEC) concentration, annual exposure due to radon and thoron, life time fatality risk and annual effective dose*

S. No.	Radon daughters conc. (C_R) (mWL)	Thoron daughters conc. (C_T) (mWL)	Annual exposure of radon (Rn) (WLM)	Annual exposure of thoron (Tn) (WLM)	Total Annual Exposure (Rn+Tn) (WLM)	Life time fatality risk factor ($x10^{-4}$)	Annual effective dose (mSv/y)
1	1.25	0.16	0.051	0.006	0.057	0.17	0.22
2	1.87	0.16	0.077	0.006	0.083	0.25	0.32
3	2.50	0.33	0.103	0.013	0.116	0.35	0.44
4	3.12	0.32	0.128	0.013	0.141	0.42	0.54
5	3.75	0.50	0.154	0.021	0.175	0.52	0.67
6	4.37	0.85	0.180	0.035	0.215	0.64	0.82
7	5.63	0.65	0.232	0.027	0.259	0.78	1.00
8	6.25	0.83	0.257	0.034	0.291	0.87	1.12
9	6.25	1.01	0.257	0.041	0.298	0.89	1.14
10	6.88	0.82	0.283	0.034	0.317	0.95	1.22
11	7.50	1.18	0.309	0.049	0.358	1.07	1.37
12	7.50	1.00	0.309	0.041	0.350	1.05	1.34
13	8.13	1.12	0.335	0.046	0.381	1.14	1.46
14	8.75	0.95	0.360	0.039	0.399	1.20	1.54
15	9.38	0.59	0.386	0.024	0.410	1.23	1.59
16	9.38	0.78	0.386	0.032	0.418	1.25	1.61
17	10.0	0.58	0.412	0.024	0.436	1.30	1.68
18	10.6	0.57	0.437	0.023	0.460	1.38	1.78
19	11.25	0.94	0.463	0.039	0.502	1.51	1.93
Average	6.54	0.70	0.269	0.029	0.298	0.89	1.15
Standard Deviation	3.05	0.31	0.126	0.013	0.134	0.40	0.52

The variation in the values may be mainly due to the contribution of building materials used in construction and ventilation condition of the dwellings. From the view of construction, we have divided the dwellings situated at ground floor (GF) in two categories. The dwellings have earthen flooring and poor ventilation conditions consider as type I while the type II dwelling have cemented flooring and good ventilation condition. The concentration of both radon and thoron in both types of dwellings is given in table 3.6. The average concentration of radon is higher (i.e. 89.23 Bq/m^3) in type I dwellings as compared with type II (i.e. 61.69 Bq/m^3). This higher value of radon in type I dwellings is due to the ground floor, which is directly constructed on top of the soil with a coating of mud. This ground floor allows more radon to diffuse inside the dwellings because of higher porosity of coating material (mud) used [Ramola et al., 1998]. Also due to the poor ventilation conditions, the radon is accumulated inside the dwelling and thus results in higher radon levels. However, in case of indoor average thoron, the values are nearly equal for both types of dwellings. Since the dosimeter was generally placed at a height of about 2.5 m from the ground, any effect of subsurface soil on indoor thoron concentration could not be detected. The main sources of indoor touring at this level are the walls of the dwelling. It was also found that the dwellings at ground floor (S. No. 7-19) have more average radon concentration than the first floor (FF) (S. No. 1-6). The reason for this increased value of radon in ground floor rooms is the sub soil emanation underneath the building [Khan et al., 1987].

We have compared our experimental values with the values reported by Chauhan [Chauhan, 2010] in the dwellings of Haryana and found that our values are lower as compared to the values given by him. The higher values reported by him is due to the fact that his study area (i.e. Panchkula and Yamunanagar) located adjacent to the Shivalik hills of Himalayas having higher uranium content [Chauhan, 2010].

Table 3.6 *Concentration of radon/thoron in type I and type II dwellings*

S. No.	Types of dwellings	No. of dwellings	Average radon concentration (Bq/m^3)	Average thoron concentration (Bq/m^3)
1	I (mud floor, poor ventilation)	07	89.23	29.49
2	II (cemented floor, good ventilation)	06	61.69	33.92

All India average levels of radon lie between 40 to 143 Bq/m^3[Kumar and Prasad, 2007]. It is clear from Table 3.4 that all the values of indoor radon concentration are well below the limit for action level recommended by ICRP i.e. 200-600 Bq/m^3 [ICRP, 1993]. All the other values are presented in tables 3.4 and 3.5, like effective dose, inhalation dose, radon progeny exposure are found under the safe limit recommended by various agencies [UNSCEAR, 2000; ICRP, 1993]. According to ICRP [ICRP, 1993] action should be taken if the values of effective dose and radon progeny exposure lie within the range of 3-10 mSv and 0.88-2.63 WLM, respectively.

3.3.4 Radon and Its Progeny in Dwellings of Bareilly City

The dosimeter cups are mounted in residential (R) and some non-residential (NR) rooms i.e. offices at the different places of study area. The results found in this study are presented in table 3.7. The values of radon concentrations have been found to vary from 51.43 – 104.34 Bq/m^3 with an average of 77.09 Bq/m^3 and a standard deviation of 16.71 while its progeny concentrations i.e. PAEC found to vary from 5.56 – 11.28 mWL with an average of 8.33 mWL and a standard deviation of 1.81. Annual exposure and life time fatality risk found to vary from 0.229 – 0.465 WLM and 0.69 x10^{-4} – 1.39 x10^{-4} with an average value of 0.35 WLM and 1.05 x10^{-4}, respectively. The effective dose to the human lungs found to vary from 0.89 – 1.80 mSv/y with an average value of 1.36 mSv/y and a standard deviation of 0.29. The concentration of radon have been found higher in non-residential rooms in comparison with the residential rooms. This may be due the fact that these non-residential rooms remain closed after the working hours. During this locked period, there could be an accumulation of radon gas, as the rooms do not have even natural ventilation because of closing of windows for the safety purpose. Another reason of increased radon levels is the use of air condition during working hours which also causes the poor ventilation.

Table 3.7 *Values of PAEC, Radon concentration, Annual Exposure, Life Time Fatality Risk and Effective dose equivalent in different residential (R) and non-residential (NR) rooms located at Ground Floor (GF) and First Floor (FF) of study area*

S.No.	Corrected track density (ρ_b) tracks/cm^2	Types of room & their location	PAEC ($WL_{conc.}$) (mWL)	Radon conc. (Rn) (Bq/m^3)	Annual Exposure (WLM)	Life time Fatality Risk (x10^{-4})	Effective dose (mSv/y)
1	330	R, FF	5.56	51.43	0.229	0.69	0.89
2	350	R, FF	5.89	54.48	0.242	0.73	0.94
3	360	R, FF	6.06	56.05	0.249	0.75	0.97
4	370	R, FF	6.23	57.63	0.256	0.77	0.99
5	380	R, GF	6.4	59.20	0.263	0.79	1.02
6	420	R, GF	7.07	65.40	0.291	0.87	1.13
7	430	R, GF	7.24	66.97	0.388	1.16	1.51
8	450	R, GF	7.57	70.02	0.374	1.12	1.45
9	480	R, GF	8.08	74.74	0.332	1.00	1.29
10	490	R, GF	8.25	76.31	0.339	1.02	1.32
11	500	R, GF	8.42	77.88	0.346	1.04	1.34
12	510	R, GF	8.59	79.45	0.353	1.06	1.37
13	540	NR, FF	9.09	84.08	0.374	1.12	1.45
14	550	NR, FF	9.26	85.66	0.381	1.14	1.48
15	570	NR, FF	9.60	88.80	0.395	1.21	1.53
16	600	NR, GF	10.10	93.42	0.416	1.25	1.61
17	610	NR, GF	10.27	95.00	0.423	1.27	1.64
18	630	NR, GF	10.61	98.14	0.437	1.31	1.69
19	660	NR, GF	11.11	102.77	0.458	1.37	1.78
20	670	NR, GF	11.28	104.34	0.465	1.39	1.80
Average			8.33	77.09	0.350	1.05	1.36
Standard Deviation			1.81	16.71	0.074	0.22	0.29

The relatively low levels of radon in residential rooms are attributed to various factors such as good ventilation condition, provision of exhaust fans, size of rooms, occupants life style etc. Several researchers have found that the indoor concentration is usually high in basements and the ground storey rooms as compared to the other higher storey rooms [Gemesi et al., 1975; Toth, 1972]. Our experimental results also show the same trends. The reason for this increased radon levels in ground storey rooms is the sub-soil emanation underneath the dwellings. Most of the dwellings shown radon concentrations below 100 Bq/m^3 while none of them shown value higher than the lower action level of 200 Bq/m^3, recommended by the International Commission on Radiological Protection [ICRP, 1993]. The other values shown in table 3.7 i.e. annual exposure, life time fatality risk and effective dose equivalent found un der the safe limit laid down by ICRP [ICRP, 1993].

3.3.5 Indoor Radon, Thoron and Their Progeny in Bareilly City

The measured values of radon, thoron and their progeny concentration, life time fatality risk and annual effective dose in different dwellings of the study area are tabulated in table 3.8. These measurements were carried out in winter season (December 2010 to February 2011). The indoor radon and thoron levels in this area are found to vary from 16.62 - 155.12 Bq/m^3 and 4.16 – 24.93 Bq/m^3 with an average value of 87.23 Bq/m^3 and 13.63 Bq/m^3, respectively. The corresponding standard deviations are 47.60 and 7.83. The average value of radon concentration (87.23 Bq/m^3) is higher than the average value of 40 Bq/m^3, reported in the dwellings worldwide [UNSCEAR, 2000]. This may be due to the difference in the concentration of radioactive elements, viz. uranium and radium in the soil and building materials of the study area. However, most of the dwellings have the radon concentration below the level of concern i. e. 150 Bq/m^3 while none of them have a value higher than the action level 200-600 Bq/m^3, recommended by ICRP [ICRP, 1993].

Table 3.8 *Values of radon, thoron and their progeny (PAEC) concentration, life time fatality risk and effective dose*

S. No.	Types of floor	Radon conc. (C_R) (Bq/m^3)	Thoron conc. (C_T) (Bq/m^3)	Ratio (C_R/C_T)	Radon progeny (PAEC) (mWL)	Thoron progeny (PAEC) (mWL)	Life time fatality risk ($x10^{-4}$)	Effective dose (mSv/y)
1	cement	55.40	9.70	5.71	5.98	0.440	0.79	1.02
2	granite	105.26	13.16	8.00	11.38	0.356	1.45	1.88
3	cement	27.70	4.85	5.71	2.99	0.122	0.33	0.50
4	cement	38.78	4.16	9.32	4.19	0.112	0.53	0.69
5	granite	127.42	24.93	5.11	13.77	0.674	1.78	2.31
6	granite	132.56	24.59	5.39	14.37	0.664	1.86	2.40
7	cement	77.56	8.31	9.33	8.38	0.224	1.11	1.38
8	granite	144.04	23.90	6.02	15.14	0.646	1.95	2.52
9	cement	16.62	5.54	3.00	1.80	0.150	0.24	0.31
10	cement	22.16	5.19	4.27	2.39	0.140	0.31	0.40
11	granite	116.34	12.47	9.33	12.58	0.337	1.60	2.07
12	granite	149.58	23.55	6.35	16.17	0.636	2.08	2.68
13	granite	121.88	18.70	6.52	13.18	0.505	1.69	2.19
14	cement	60.94	9.35	6.52	6.59	0.253	0.84	1.09
15	cement	33.24	4.50	7.39	3.59	0.122	0.46	0.59
16	granite	155.12	23.20	6.69	16.77	0.627	2.15	2.78
17	granite	110.80	12.81	8.65	11.97	0.346	1.52	1.97
18	cement	44.32	10.38	4.27	4.79	0.280	0.62	0.81
19	granite	138.50	24.24	5.71	14.97	0.655	1.93	2.50
20	cement	66.48	9.07	7.33	7.19	0.245	0.92	1.19
Minimum		16.62	4.16	3.00	1.80	0.112	0.24	0.31
Maximum		155.12	24.93	9.33	16.77	0.674	1.21	2.78
Average		87.23	13.63	6.53	9.41	0.377	2.15	1.56

The radium content in the soil of Bareilly city lies within the range of 11- 40 Bq/kg, which is much below than the Organization for Economic Co-operation and Development [OECD, 1979] recommended value of 370 Bq/kg. As radon is the daughter product of radium therefore low level of radium in soil resulting low level of indoor radon and it is very well reflected in our present study. Table 3.9 shows the values of radon concentration from different parts of India. We have also compared our indoor radon results with the other countries (table 3.10). In the present study the radon/thoron (C_R/C_T) ratio is found to vary from 3.0 to 9.33 with an average of 6.53. This ratio finds good agreement with the ratio (5.1 to 9.0) reported for the dwellings of Brahmaputra valley of Assam [Deka et al., 2003]. However some other parts of India like Shilong, Karimganj, Aizwal and Agartala have the ratio between 2.0 to 5.0 (approx.) [Dwivedi et al., 2001]. The annual effective dose received by the residents of studied areas varies from 0.31 to 2.78 mSv/y with an average of 1.56 mSv/y and a standard deviation of 0.85. In all the dwellings surveyed, the maximum annual effective dose (2.78 mSv/y) is found less than the lower limit of the action level (3 mSv/y) recommended by ICRP [ICRP, 1993]. The lifetime fatality risk of the residents of the studied area varies from 0.24 $x10^{-4}$ to 1.21 $x10^{-4}$ with an average of 2.15 $x10^{-4}$ and a standard deviation of 0.66. It is clear from table 3.8 that the values of radon concentration are higher than thoron. It may be due to the difference in half life of radon and thoron, which affects the exhalation rate from the wall and the concentration distribution inside the dwellings. The other reason may be that the dosimeter was generally placed at a height of about 2.5 meters from the ground; any effect of floor/subsurface soil on thoron concentration could not be detected. Hence in that condition the main sources of indoor thoron are only the walls of dwellings [Verma and Khan, 2013]. The difference in the values of radon concentration may be due to the wide variation in ventilation conditions, types of construction and other factors such as

Table 3.9 *Comparison of indoor radon levels with different parts of India*

S. No.	Indoor Radon level (Bq/ m^3)	Area	No. of measurements	References
1	12-104	Faizabad (U.P.)	20	[Verma, and Khan, 2013]
2	12-190	Jodhpur (Rajasthan)	20	[Kumar et al., 1991]
3	15-218	Amritsar (Punjab)	32	[Virk and Sharma, 2000]
4	13-143	All India	-	[Ramachandran, 1998]
5	66-104	Northern Haryana	80	[Chauhan, 2010]
6	36-140	Hamirpur and Una (HP)	22	[Virk and Sharma, 2002]
7	18-62	Jaipur(Rajasthan)	10	[Sharma et al., 2012]
8	17-155	Bareilly (U.P.)	20	[Verma, and Khan, 2014 (In press)]

Table 3.10 *Comparison of indoor radon levels with different countries*

S. No.	Country	Average Indoor radon level (Bq/m^3)	References
1	India (Bareilly)	87	[Verma, and Khan, 2014 (In press)]
2	Czech Republic	140	[UNSCEAR, 1993]
3	Spain	86	[UNSCEAR, 1993]
4	Finland	123	[Castren, 1994]
5	Austria	97	[Friedmann et al., 2001]
6	Belgium	48	[Zhu et al., 2001]
7	France	68	[Baysson et al., 2003]
8	Ireland	89	[Fennel et al., 2002]
9	Italy	70	[Bochicchio et al., 1996]
10	Luxembourg	115	[Kies et al., 1996]
11	Romania	112	[Szacsvai et al., 2013]
12	Sweden	108	[Swedjemark and Hubbard, 1993]
13	Turkey (Giresun)	130	[Celik et al., 2008]
14	USA	46	[EPA, 1992c; Marcinowski et al., 1994]

temperature, humidity etc. In the study area, most of the dwellings having brick walls, concrete roofs and cemented floors. However, there are some differences i.e., a) some houses have plastered and painted walls, while others have walls without plaster and paint, b) some houses have floor made of granite, while others have the simple cemented floor. The higher values of radon (>100 Bq/m^3) found in those types of dwellings who have the granite flooring. As we know granite is a rich source of radium (^{226}Ra) which further decay to radon (^{222}Rn) by alpha emission, so it may be a reason for higher concentration of radon in these dwellings. The use of Air Condition (A.C.) in the above said dwellings are making poor ventilation, which is also an important reason of higher radon levels. However, it is clear from table 3.8 that lower concentrations of radon (< 80 Bq/m^3) found in the houses having the cemented floor. Also the proper ventilation in these dwellings provides circulation of air from inside to outside and vice versa which results the low concentration of radon. Figure 3.1 shows the frequency distribution of the measured radon concentration among the dwellings of the study area. The number of houses (%) having the radon concentration ranges from 0–75, 75–150 and >150 Bq/ m^3 are 45%, 50% and 5%, respectively. The maximum value of radon progeny (16.77 mWL) found in the present study is below the recommended maximum level of 21.50 mWL in India [Ramachandran, 1998; Ramachandran and Subba Ramu, 1994].

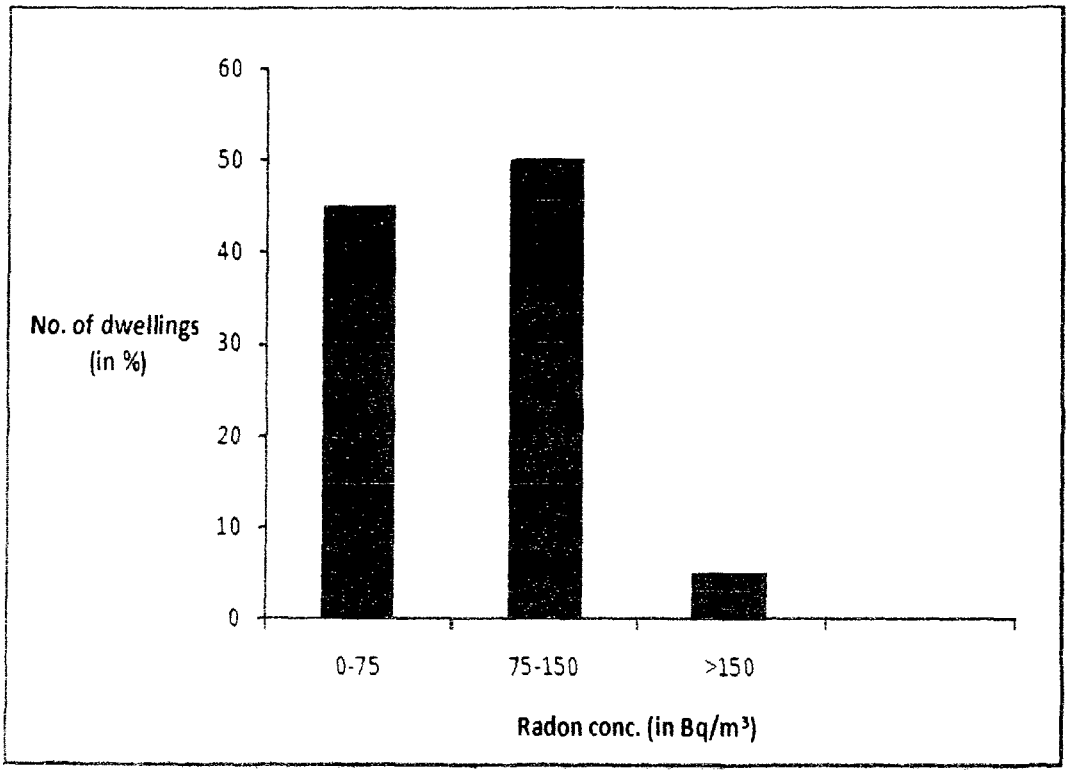

Figure 3.1 *Numbers of dwellings (in %) having different concentration of radon*

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CHAPTER-IV

MEASUREMENTS OF RADON EXHALATION RATE AND RADIUM CONTENT IN FARRUKHABAD AND FAIZABAD CITY

4.1 Introduction

The largest contributor of ionizing radiation to the population is natural radioactivity. It is present everywhere in varying concentrations. The natural radiation sources such as granites, soils, sand, water and food items contribute about 80% radiations dose received by human beings [UNSCEAR, 1993]. Soil is the main source of continuous radiation exposure to humans. It acts as a medium of migration for transfer of radio-nuclides in our environment. Hence, the soil is the basic indicator of radiological contamination in the environment [Ibrahim et al., 2009]. The naturally occurring radio-nuclides present in the soil are mainly ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K. These radionuclides cause external and internal exposure. External exposure is caused by the gamma activity of radionuclides in the ground and construction material, whereas internal exposure results from the inhalation and ingestion of naturally occurring radionuclides in air and diet. The main source of inventory of radionuclide into the food cycle is cesium (^{137}Cs). It is very difficult to exactly pinpoint the source of contamination. Another important source of internal exposure is the α-radioactive noble gas radon (^{222}Rn), which is the sixth daughter in the decay chain of Uranium-238 (^{238}U). Being a noble gas and having relatively long half life (3.82 days), radon can easily enter into our living environment. Emission of radon per unit area per unit time is known as exhalation rate. It is of two types; surface exhalation rate and mass exhalation rate. There are several factors which affect the radon exhalation rate i.e. soil parameters such as moisture, porosity, permeability and grain size, but the most important is the radium content of the bedrock

or soil [Khayrat et al., 2001; Shweikani et al., 1995].

Radium (^{226}Ra) is considered to be one of the most hazardous of all natural radio nuclides present in the environment, primarily due to its decay by alpha emission and its long half-life. Radium is present at low concentrations in food and water which is the most important pathway of its ingestion; consequently, humans routinely ingest and retain its small quantity. After entering into the human body, it tends to follow calcium in metabolic processes to become concentrated in the bones. The radiation given off by radium bombards the bone marrow and destroys tissue that produces red blood cells. Radium is absorbed from the soil by plants and passed up the food chain to humans. As radon is the daughter of radium, so the radium content of the sample contributes to the levels of environmental radon [Khan et al. 2011]. It is estimated that average worldwide effective dose equivalent from a natural source of radiation, in areas of normal background, is 2.4 mSv, of which 1.75 mSv is contributed by radon [UNSCEAR, 1993].

The radon exhalation rate is of prime importance in the estimation of various solid waste materials. The radon exhaling properties of porous material, both naturally occurring like soil, coal, sand and rocks and man-made like mining wastes, fly ash and many building materials etc. have been the subject of several investigators [Jonassen, 1983; Varshney et al., 2010; Mahur et al., 2008]. Various studies related to soil radioactivity were carried out in many countries [Tzortzis et al., 2003; Khatir et al., 1988; Matiullah et al., 2004; Ramli et al., 2005; Veiga et al., 2006]. Being aware of the importance of radium and of radon exhalation, we have carried out their measurements in soil samples of Farrukhabad and faizabd cities.

4.2 Measurement of Radon Exhalation Rate and Radium Content in Soil

4.2.1 Experiment Details

We used the well-established "can technique" - a simple passive detection system using LR-115 type II solid-state nuclear track detectors for the measurement of radium content and radon exhalation rate in soil samples. The soil samples have been taken from the different places of study area by grab sampling method. The samples were dried in an oven at 100^0 C for 1-2 hours to remove the moisture content completely. These dried soil samples are finely powder and sieved through a sieve of 150 mesh size. About 100 g of powdered sample was placed at the bottom of a cylindrical Can of size 7 cm diameter and 10 cm height (figure 4.1), and sealed for 30 days so as to attain the equilibrium among radium and its daughter products. After one month, the detector of size 2 x 2cm^2 are fixed at the lower surface of the lid of Can in such a way that its sensitive surface faced the sample, so that it record the tracks of alpha particles resulting from the decay of radon gas produced through the α decay of radium. Theirafter, the Cans have sealed and left about 90 days for exposure. The tracks due to alpha particles of radon have registered on the detector. These detectors have etched in 2.5 N NaOH solution for about 90 min, at 60 ^{0}C, and washed for about 5 min in running water. The numbers of alpha tracks has been counted by using an optical microscope at a magnification of 100X. The track density ρ (tracks/cm^2) is related to the radon concentration C_{Rn} (in Bq/m^3) and the exposure time T by the formula [Somogyi, 1986]

$$\rho = KC_{Rn}T \qquad (1)$$

Where K is the sensitivity factor (tracks.m^3/Bq.cm^2.s) of LR-115 plastic track detector with an uncertainty of about ±15%. The value of K depends on the radius and height of the used Can [Somogyi, 1986].

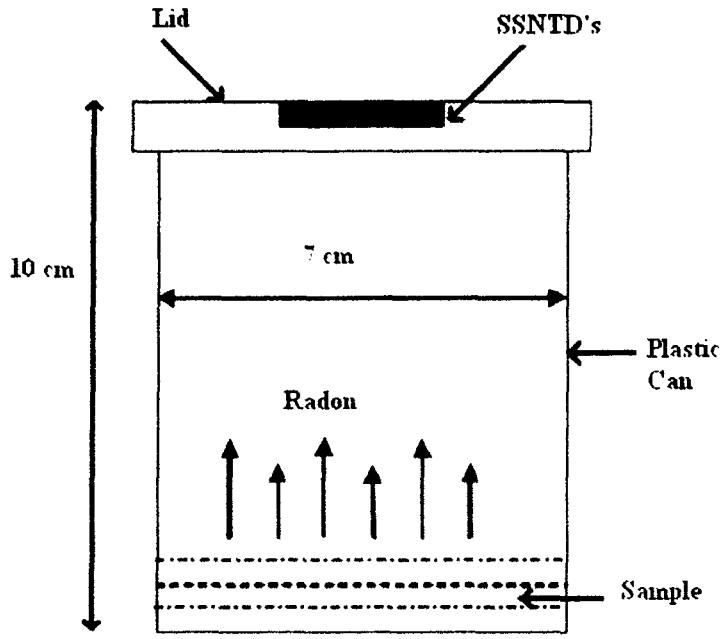

Fig. 4.1 Experimental set-up for the measurement of radon exhalation rate and radium content

4.2.2 Theoretical Consideration

Since the half-life of ^{226}Ra is 1620 years and that of ^{222}Rn is 3.82 days, it is reasonable to assume that an effective equilibrium (about 98%) for radium-radon members of the decay series is reached in about three weeks. Once the radioactive equilibrium is established, one may use the radon alpha analysis for the determination of steady state activity concentration of radium. The activity concentration of radon (C_{Rn}) begins to increase with time T, after the closing of the can, according to the relation

$$C_{Rn} = C_{Ra}\left(1 - e^{-\lambda_{Rn} T}\right) \qquad (2)$$

Where C_{Ra} is the effective radium content of the sample and λ_{Rn} is the half life of radon. Since a plastic track detector measures the time-integrated value of the above expression, i.e. the total number of alpha disintegrations in unit volume of the can with a sensitivity K during the exposure time T, hence the track density observed is given by

$$\rho = KC_{Ra} T_e \qquad (3)$$

Where Te denotes, by definition, the effective exposure time given by

$$T_e = \left[T - \lambda_{Rn}^{-1}\left(1 - e^{-\lambda_{Rn} T}\right)\right] \qquad (4)$$

Referring to figure 4.1 it is clear that the "effective radium content" of the soil samples can be calculated by using the relation [Azam et al., 1995; Mahur et al., 2008; Khan et al., 2011]

$$C_{Ra}\,(Bq/kg) = \left(\frac{\rho}{KT_e}\right)\left(\frac{hA}{M}\right) \qquad (5)$$

Where h is the distance between the detector and the top of soil samples (m), A is the area of a cross section of the Can (m^2), M is the mass of the soil sample (kg). The mass exhalation rate of the sample for release of radon can be calculated by using the expressions [Khan et al., 2011]

$$E_X(M)(Bq/Kg.d) = C_{Ra}\left(\frac{\lambda_{Ra}}{\lambda_{Rn}}\right)\frac{1}{T_e} \qquad (6)$$

Where λ_{Ra} is the half life of radium. The surface exhalation rate of the sample for release of radon can be calculated by using the expressions [Khan et al., 2011]

$$E_X(S)(Bq/m^2.d) = \left[C_{Ra}\left(\frac{\lambda_{Ra}}{\lambda_{Rn}}\right)\frac{1}{T_e}\right]\frac{M}{A} = E_X(M)\times\frac{M}{A} \qquad (7)$$

4.2.3 Results and Discussion

4.2.3.1 Radium Content and Radon Exhalation Rate in the Soil of Farrukhabad City

The measured values of radium content and radon exhalation rates in soil samples collected from the study area are shown in table 4.1. The radium content in soil samples have been found to vary from 5.39 to 34.56 Bq/kg with an average value of 16.58 Bq/kg and a standard deviation of 7.16. Table 4.1 also shows the value of radon exhalation rates in terms of mass and surface area. The mass exhalation rate has been found to vary from 0.41×10^{-6} to 2.64×10^{-6} Bq/kg.d with a mean value of 1.26×10^{-6} Bq/kg.d and standard deviation of 0.54 while the surface exhalation rate is found to vary from 1.41×10^{-6} to 9.10×10^{-6} Bq/m^2.d with a mean value of 4.35×10^{-6} Bq/m^2.d and standard deviation of 1.89. The value of the radium content in soil samples found lower than the values reported by many researcher [Khan et al., 2009; Singh et al., 2002; Sharma et al., 2003], whereas the values of radon exhalation rate in both cases are quite low as compared to values reported by khan et al. in the soil of Lucknow [Khan et al., 2009]. The values of radium content were also found lower than the permissible value i.e., 370 Bq/kg [OECD, 1979]. From table 4.1, it has been observed that there are variations in the values of radon exhalation rates among the samples. This variation may be arising due to the difference in the nature of the samples, and radium content of the samples [Barooah et al., 2009] because the radium is present in varying levels all over the world.

Table 4.1 *Values of "effective radium content" and "radon exhalation rate" in soil samples collected from the study area*

S. No.	Detector code	Corrected track density (Track/cm^2)	Effective radium content (Bq/kg)	Mass exhalation rate Ex(M) × 10^{-6} (Bq/kg.d)	Surface exhalation rate Ex(S) ×10^{-6} (Bq/m^2.d)
1	D-11	680	5.39	0.41	1.41
2	D-13	790	6.26	0.47	1.62
3	D-22	860	6.81	0.52	1.79
4	D-21	1380	10.94	0.83	2.86
5	D-25	1410	11.17	0.85	2.93
6	D-23	1500	11.89	0.90	3.10
7	D-24	1600	12.68	0.96	3.31
8	D-05	1610	12.76	0.97	3.34
9	D-16	1700	13.47	1.02	3.51
10	D-14	1850	14.66	1.12	3.86
11	D-09	1880	14.90	1.13	3.89
12	D-10	1940	15.38	1.17	4.03
13	D-12	1950	15.46	1.18	4.06
14	D-15	2000	15.85	1.21	4.17
15	D-17	2110	16.72	1.27	4.37
16	D-18	2180	17.28	1.32	4.55
17	D-08	2300	18.23	1.39	4.79
18	D-01	2310	18.47	1.41	4.86
19	D-07	2380	18.87	1.44	4.96
20	D-20	2560	20.29	1.55	5.34
21	D-03	2590	20.53	1.56	5.37
22	D-19	2680	21.24	1.62	5.58
23	D-04	3590	28.46	2.17	7.48
24	D-02	4080	32.28	2.46	8.48
25	D-06	4360	34.56	2.64	9.10
Average			16.58	1.26	4.35
Standard Deviation			7.16	0.54	1.89

This work is important because this area has been studied first time by us for such measurements to know about the radiation level present in the environment.

4.2.3.2 Radium Content and Radon Exhalation Rate in the Soil of Faizabad City

Table 4.1 depicts the values of the radium content of soil samples collected from different locations of the Faizabad city of Uttar Pradesh state in Northern India. It is clear from the table 4.2 that the values of radium content varies from 08.91 to 20.80 Bq/kg with an average value of 13.16 Bq/kg and a standard deviation of 4.21. Present study explain the values of the radium content in soil are lower than the values determined by the other researcher for Indian soil [Khan et al., 2011; Khan et al., 2009; Sharma et al., 2003; Singh et al., 2002]. Table 4.2 also presents the value of mass exhalation and surface exhalation rates of radon of soil samples. The mass exhalation rates have been found to vary from 0.56 x 10^{-6} to 1.58 x 10^{-6} Bq/kg.d with an average value of 1.0 x 10^{-6} Bq/kg.d and a standard deviation of 0.32. The surface exhalation rates have been found to vary from 1.93 x 10^{-6} to 5.44 x 10^{-6} Bq/m^2.d with a mean value of 3.38 x 10^{-6} Bq/m^2.d and a standard deviation of 1.17. These experimental values of radon exhalation rates in soil samples are quite low as compared to those reported in the soil of Lucknow [Khan et al., 2009].

The values of radium concentration are also less than the permissible value of 370 Bq/kg as recommended by the Organization for Economic Cooperation and Development [OECD, 1979]. The variations in the values of radium may be due to the radium content of the samples, porosity and density of the samples. The differences in the nature of the samples, the emanation factor of radon from the samples and the diffusion coefficient of radon in the different samples are the othe factors that affect the radium content in soil samples [Ramachandran and Suba Ramu , 1989; Folkerts et al., 1984].

Table 4.2 *Values of Radium Content, Mass Exhalation and Surface Exhalation Rates of Radon in Soil samples collected from the study area*

S.No.	Detector Code	Corrected track density (Tracks/cm^2)	Radium Content (Bq/kg)	Mass Exhalation Rate Ex (M) $\times 10^{-6}$ (Bq/kg d)	Surface Exhalation Rate Ex (S) $\times 10^{-6}$ (Bq/m^2 d)
1	D-01	2180	17.50	1.33	4.58
2	D-11	1970	15.82	1.20	4.13
3	D-03	2590	20.80	1.58	5.44
4	D-13	2550	20.47	1.56	5.37
5	D-09	1390	11.16	0.85	2.93
6	D-04	1110	08.91	0.68	2.34
7	D-02	1700	13.65	1.04	2.54
8	D-10	1540	12.36	0.94	3.24
9	D-05	2030	16.30	1.24	4.27
10	D-06	1520	12.20	0.93	3.20
11	D-08	1590	12.76	0.97	3.34
12	D-07	1130	09.07	0.69	2.37
13	D-12	1210	09.71	0.74	2.55
14	D-14	1150	09.25	0.70	2.41
15	D-15	930	07.46	0.56	1.93
Average			13.16	1.00	3.38
Standard Deviation			4.21	0.32	1.17

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CHAPTER-V

CONCLUSIONS

This chapter presents a brief summary and the main conclusions of the studies carried out during this Ph.D. research work. The present thesis is based on the experimental work carried out in the field and in the Laboratory. The first two chapters described basic introductory techniques of the solid state nuclear track detectors, materials and methods used during the experimental work and geological information about the area studied. We have divided the experimental work into two parts. The first part consists the results of indoor radon, thoron and their progeny measurements by using dosimeters cups fitted with LR-115 type-II solid state nuclear track detectors. In the second part we presents the results of radium and radon exhalation rates in some soil samples by using "close can" technique. A lot of research work has been performed during the past in India and around the world for indoor and outdoor radon measurement. Most of that research work is carried out in order to the health risk associated with these radionuclides. The data reported by the researcher shown wide variation in their values of indoor radon. In the present work we study the radon, thoron and their progeny levels in the dwellings of Farrukhabad, Faizabad and Bareilly city of Northern India. We also calculate the outdoor radium content and the radon exhalation rate in soils of Farrukhabad and Faizabad cities. The main conclusions drawn from the present study are as follows:

- In present study the radon levels almost lies within all India levels of radon i.e. 40 to 143 Bq/m^3. Based on the ICRP recommended range of 200-600 Bq/m^3 and EPA action level of 148 Bq/m^3, one can say that radon levels in all the study areas are under the safe limit.
- The minimum average value of indoor radon concentration has been found to be 59 Bq/m^3 in Faizabad while maximum average value of 87.23 Bq/m^3 are found in

Bareilly city. These average values are higher than the world average value of indoor radon level (40 Bq/m^3). The reason of this higher value of radon may be the higher radium present in the soil beneath the dwellings, their construction type and the ventilation system.

- The values of thoron concentration in all the dwellings of the study area varies from 6 to 50 Bq/m^3 which is comparable to the thoron concentration of 5.7 to 42.2 Bq/m^3 reported for Indian dwellings.
- The average value of indoor thoron concentration in each study area have been found higher than the world average of 3 Bq/m^3.
- The maximum value of radon progeny (PAEC) in the study i.e. 16.77 mWL has been found below the recommended maximum level of 21.50 mWL in India.
- The values of effective dose in some dwellings of Bareilly city have been found higher than the worldwide average radiation dose of 2.4 mSv/y, but less than the lower limit of action level 3 mSv/y recommended by ICRP.
- Dwellings having the earthen floor shown higher values of radon and PAEC as compared to cement floor or the floor covered with any covering material. The radon level is nearly two times higher in the dwellings having earthen floor.
- Lower values of indoor radon and PAEC observed in the dwellings having plastered wall and painted with good quality paints.
- The dwellings situated at ground floor have more average radon concentration than the first floor. The reason of this increased value is the sub soil emanation underneath the buildings.
- Relatively higher level (about two times) of radon have been found in non-residential rooms in comparison with the residential rooms. It is due to the poor ventilation condition occurred in non-residential rooms.

- ❖ Ventilation condition plays an important role to decide the indoor radon levels.
- ❖ Radon levels decrease with the increase in height from the ground surface.
- ❖ The values of radon and its progeny concentration are found more in bare mode in comparison to membrane mode.
- ❖ By providing good ventilation condition, covering the floor and walls with good quality covering materials, radon and their progeny levels can reduce inside the dwellings.
- ❖ Soil of Farrukhabad city have shown higher radon exhalation rate and radium content as compared to Faizabad.
- ❖ Our values for radium content in soil samples lie within the range 2.5 - 207.0 Bq/kg reported in Indian soil. The maximum value of the radium content of our study has been found much less than for safe use (i.e. 370 Bg/kg) laid down by Organization for Economic Co-operation and Development (OECD).
- ❖ The radon exhalation rate is mainly influenced by texture and porosity of soil.

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1) **Deepak Verma**, M. Shakir Khan (2014): Assessment of indoor radon, thoron and their progeny in dwellings of Bareilly city of northern India using plastic track detectors. *Romanian J of Physics, 59, 1-2 (In press).*

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